TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

Cylinders metal - Instability
Bending & Shear - Cylinders

No. 910

SOME INVESTIGATIONS OF THE GENERAL INSTABILITY OF STIFFENED METAL CYLINDERS

VI - STIFFENED METAL CYLINDERS SUBJECTED TO COMBINED BENDING AND TRANSVERSE SHEAR

Guggenheim Aeronautical Laboratory
California Institute of Technology

Washington
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This is the sixth of a series of reports covering an investigation of the general instability problem by the California Institute of Technology. The first five reports of this series cover investigations of the general instability problem under the loading conditions of pure bending and were prepared under the sponsorship of the Civil Aeronautics Administration. This report and the succeeding reports of this series cover the work done on other loading conditions under the sponsorship of the National Advisory Committee for Aeronautics.

SUMMARY

This report summarizes the work that has been carried on in the experimental investigation of the problem of general instability of stiffened metal cylinders subjected to combined bending and transverse shear at the C.I.T. This part of the investigation includes tests on 55 sheet-covered specimens. Under a loading of combined bending and transverse shear, the failure of the specimens is characterized by two distinct types of failure, namely, a bending or a shear failure. It has also been determined that the failing loads of the specimens have not been influenced by the length of the specimens.

INTRODUCTION

It is intended to give, in this report, a summary of the experimental investigation of the general instability of stiffened metal cylinders subjected to combined bending and transverse shear. The earlier work t C.I.T. on the problem of general instability of stiffened metal cylinders has been reported in references 1, 2, 3, 4, and 5. A total of 55 sheet-covered specimens has been tested to determine the effects of the combined loading of bending plus transverse shear and to determine the influence of length on the failing load.

INVESTIGATION OF LENGTH EFFECT

Inasmuch as all the pure bending specimens had a length to diameter ratio of 2.0, it was necessary to determine whether the failing loads of these specimens were influenced by the length. The purpose of this investigation was, therefore, to determine the length to diameter ratio L/D at which the failing load becomes independent of length.

Eight specimens having L/D ratios of 1.2, 1.6, 2.0, and 2.6 were tested, four in which the frame spacing was 2.0 inches and four in which the spacing was 4.0 inches. The spacing of the longitudinal and diameters was the same for all specimens, 2.62 and 20 inches, respectively.

The curves of unit strain as a function of the applied bending moment are shown in figures 7 to 11. The test procedure and method of strain measurements have been described in detail in references 2 and 4.

The failing strain as a function of the L/D ratio is shown in figure 2. It is seen that the specimens having an L/D ratio of 2 and 2.5 failed at approximately the same strain. As the L/D ratio decreases the failing strain increases somewhat and at an L/D ratio of 1.2 the increase is 12 and 23 percent for the 4- and 2-inch frame spacings, respectively. From these test results it can be concluded that the failing loads of the pure bending specimens used in the previous experiments were not influenced by the length.

INVESTIGATION OF COMBINED BENDING AND SHEAR

Description of Testing Apparatus

The testing machine, as shown in figure 71, consists essentially of four separate elements - the bed, the fixed end plate, the movable carriage, and the loading beam. The bed is $12\frac{1}{2}$ feet long, $3\frac{1}{2}$ feet wide, and is constructed of heavy I-beams. To one end is rigidly bolted the fixed end plate. The loading beam is a built-up box section 6 feet long - although this can be extended by splicing on additional lengths. Bolted to one end is an end plate similar to the fixed end plate. The loading beam is freely suspended in a cage or carriage which itself is free to move along the bed. The beam is suspended from two knife edges at the top of the carriage and is balanced by counterweights. With this arrangement the weight of the loading beam and end plate will not be carried by the specimen, but will always be just balanced by the counterweights.

One end of the specimen is bolted to the fixed end plate - the other to the end plate on the loading beam. A vertical upload is then applied at any desired point on the loading beam by means of a screw jack. The load is indicated by a dial gage mounted on a dynamometer which was previously calibrated in a 150,000-pound Tinius Olsen testing machine.

Method of Strain Measurement

Resistance strain gages were used to measure the strain at desired points. Essentially, this method measures the change in resistance of a wire element cemented to the specimen. The gages were calibrated by cementing a wire element of known length to a test bar and measuring the change in resistance for a known unit strain.

The gages were mounted on the neutral axis of the stiffeners and were also mounted in pairs - one on each side of the stiffener - so that the mean reading would be unaffected by bending. The resistances were measured with a Wheatstone bridge, the voltage being supplied by two dry cells. The gages were cut in and out of the bridge circuit through a mercury switch arrangement, thus avoiding large contact resistances.

During the early part of the investigation, a 3-inch-gage length was used. However, it was found that this small gage length was apparently quite sensitive to small local deformations. Also it seemed probable that the behavior of the gage was unduly influenced by the conditions at the juncture points where the leads were soldered. It was therefore decided to adopt a 16-inch-gage length. Although this gage did not permit measuring the strain at as many different points as the 3-inch gage, it yielded more consistent results.

Test Prodedure

The specimen was mounted in the testing machine and the loading jack placed at the proper position to give the desired moment arm. The load was then applied in increments, the jack-dial reading and the strain-gage resistances being recorded for each increment. Also, over-all strain measurements were made at the top, bottom, and sides by means of dial gages. The over-all measurements on the sides were useful in detecting loading eccentricities. The behavior of the specimen was carefully noted as the test progressed; initial and subsequent buckles were observed and their positions, extent, and corresponding loads recorded.

Combined Loadings

In the pure bending tests, the problem of determining the maximum strain associated with the failing load was relatively simple because of the uniform loading over the length of the specimen. However, when the test specimen is subjected to combined bending and transverse shear the bending moment and the corresponding strains vary over the length of the specimen. Hence, the method of measuring, over the specimen length, a maximum mean strain at failure and assigning this measured strain to the failing load can no longer be applied. The variation of strain and the end conditions of the specimen make it particularly difficult to associate a particular strain with the failing load. The maximum moment occurs at the fixed end; however, this maximum moment and the corresponding strain cannot be considered as being a measure of the ultimate strength of the cylinder because of the fixed-end conditions.

There are two possible methods of presenting the test data. One method would be to measure the strain at a number of points along the length of the specimen, which could then be presented as the existing strain condition along the length of the specimen when failure occurred. Another method would be to measure the failing strain at the point at which the first buckle appears during the loading process and to consider this to be indicative of the maximum strain to which the specimen can be subjected before failure occurs.

Both methods have certain disadvantages. The first does not lend itself readily to application in practical design. It is customary, for maximum structural efficiency, to design a reinforced cylindrical structure in such a manner as to keep the stress nearly constant even though the bending moment is variable. This is usually accomplished through the geometrical taper of the section and also by tapering the effective bending material. For this reason, the designer is mostly interested in a single value of the allowable stress or strain for calculating his margins of safety. From this point of view the second method is preferable. However, the main objection here is that the validity of associating the strain condition at a point with the failure of the cylinder may be questionable.

This latter method has also one other advantage; namely, for the pure bending failure a parameter has been derived which appears to be satisfactory. In determining the influence of the transverse shear on the maximum strain at failure, it is convenient to have a single value of the strain for combined bending and shear to compare with the strain value for pure bending.

In view of the above, the following method of presentation was adopted. It was found that the initial buckle or buckles appeared over a relatively short range, being on the average about 14 inches from the fixed end for the 32-inch-diameter cylinders and 10 inches for the 20-inch-diameter cylinders. For this reason the strain at failure was considered to be the average of the strain measurements obtained with the 3-inch-wire gage over a distance extending from about 4 to 24 inches from the fixed end, or the strain measurements of the 16-inch-wire gage which extended from 6 to 22 inches from the fixed end.

The type of failure in combined bending and shear differs particularly in one respect from that of the pure bending failure. For the combined loading the failure is, in many cases, gradual - that is, the buckles, although extending over several frames and longitudinals, slowly increase in depth and size with increasing load until a sudden collapse occurs with a marked increase in depth and size of the buckle or buckles. In the case of the pure bending specimens, the original cross-sectional shape is closely maintained until failure occurs - the failure being particularly violent and accompanied by large and deep buckles with as much as a two-thirds drop in the applied load.

From a visual observation of the failure, it appeared, during the early part of the investigation, that failure of a specimen was either of the bending or the shear type; that is, the beginning of a failure was confined to either a region of maximum compression or a region of maximum shear. The rather definite separation of the regions of failure would indicate that when a failure occurred in the compression region the failure would be nearly independent of the applied shear and would depend primarily on the state of compression strain; whereas, when failure occurred in the region of maximum shear the failure would be independent of the state of compression strain and only depend on the applied shear.

The above observations were borne out by the experimental results. In figure 3 are plotted the ratios of the compressive strain ϵ/ϵ_o as a function of VR/M for a number of specimens of both 16-inch and 10-inch radius. In these expressions,

ϵ maximum compressive strain value (at the position previously described) for the combined loading condition

ϵ_o same strain value for pure bending

V applied shear

R radius of the specimen

M bending moment

Since $M = VL$, where L is the distance from the applied shear load to the point where the strain is measured, it is seen that the ratio VR/M is equivalent to R/L. This presentation is merely to indicate that when the failure occurs in the compression region the maximum compressive strain is independent of the applied shear. For these specimens, the applied shear load varied from 503 to 1450 pounds for the 16-inch-radius specimens and from 710 to 2310 pounds for the 10-inch specimens. The minimum moment arm L was limited by the length of the specimen.

In figure 4 are plotted ratios of ϵ/ϵ_0 as a function of V/V_0 for one series of tests, where V_0 is the shear load which causes a pure shear failure and V is the shear load corresponding to ϵ. It is seen from this figure that specimens 116 and 117 failed at the same shear load but widely different values of ϵ (i. e., bending moment). The photographs (figs. 75 and 76) indicate that specimen 116 failed similtaneously by combined bending and shear, whereas specimen 117 failed in shear. It appears from these results that the interaction curve for this type of loading consisted essentially of two perpendicular straight lines. The photographs (figs. 72 to 74) also show types of failure.

The strains at failure, for the specimens which failed by bending, have been compared with the parameter obtained for the pure bending failures and are shown in figure 5. The test values follow the same trend as the curve for the pure bending failures; however, the experimental scatter is somewhat greater than for the pure bending specimens. It is felt that this scatter is primarily due to the following:

(a) The accuracy of the strain measurements depends on the reliability of the electric strain gages and an accuracy greater than 5.0 percent is not to be expected.

(b) Adopting a strain value at a constant distance from the fixed end as being indicative of strain at failure also leads to some inaccuracies.

A number of curves showing the variation of strain in the longitudinal direction are shown in figures 67 to 69. The distribution of normal stresses is shown for a number of specimens in figures 64 to 66. In table I the experimental and computed data are given for each specimen. The curves of strain against applied shear are shown in figures 12 to 63. The strain-gage position and the stringer number is indicated in tabular form for each set of curves. The method of numbering the stringers is indicated in figure 6.

In all specimens the longitudinal stringers were S_1 and the frames F_5 with the exception of specimens 126 and 127 in which the longitudinals were S_2 and the frames F_5. The cross-sectional dimensions of the longitudinals and frames are shown in figure 1. The variations of the sectional parameters, ρ and I, for the longitudinal S_2 with a variation in effective width are shown in figure 70.

CONCULUSIONS

The experimental results indicate that for combined bending and transverse shear, the failure is characterized by two distinct types of failure, namely, a bending or a shear failure. If the failure is bending, the failing strain can be predicted with sufficient accuracy by means of the pure bending parameter. However, it is still necessary to determine a shear failure parameter in order to ascertain when a bending or a shear failure will occur. Because of the limitation imposed by the specimen length on the maximum shear which could be applied, it was quite difficult to obtain shear failures. In the combined bending and torsion experiments additional data on shear failures will be obtained which may be sufficient to lead to a suitable shear parameter.

Guggenheim Aeronautical Laboratory,
California Institute of Technology,
Pasadena, Calif., June 10, 1942

REFERENCES

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2. Guggenheim Aeronautical Laboratory, California Institute of Technology: Some Investigations of the General Instability of Stiffened Metal Cylinders. II - Preliminary Tests of Wire-Braced Specimens and Theoretical Studies. T.N. No. 906, NACA, 1943.

3. Guggenheim Aeronautical Laboratory, California Institute of Technology: Some Investigations of the General Instability of Stiffened Metal Cylinders. III - Continuation of Tests of Wire-Braced Specimens and Preliminary Tests of Sheet-Covered Specimens. T.N. No. 907, NACA, 1943.

4. Guggenheim Aeronautical Laboratory, California Institute of Technology: Some Investigations of the General Instability of Stiffened Metal Cylinders. IV - Continuation of Tests of Sheet-Covered Specimens and Studies of the Buckling Phenomena of Unstiffened Circular Cylinders. T.N. No. 908, NACA, 1943.

5. Guggenheim Aeronautical Laboratory, California Institute of Technology: Some Investigations of the General Instability of Stiffened Metal Cylinders. V - Stiffened Metal Cylinders Subjected to Pure Bending. T.N. No. 909, NACA, 1943.

TABLE I

Test	Long Spacing b	Frame Spacing d	Radius	Ultimate Applied Shear	Moment arm - to fixed end.	Strain at Failure	$\sqrt[4]{bd}$	ρ_x	ρ_y	$\sqrt[4]{(\rho_x\rho_y)^3}$	$\frac{\sqrt[4]{bd}}{\sqrt[4]{(\rho_x\rho_y)^3}}R$	$\sqrt[4]{\frac{(\rho_x\rho_y)^3}{bd}}\frac{1}{R}$	Type of Failure
75	5.06	8"	16"	1067#	128"	.00161	2.52	.1167	.02335	.0119	3390	2.95x10-4	Gen. Instability
76	"	"	"	1050	116"	.00153	"	.1167	.02335	.0119	3390	2.95 "	"
77	"	"	"	1450	92"	.001516	"	.1167	.02335	.0119	3390	2.95 "	"
78	"	"	"	995	116	.00151	"	.1167	.02335	.0119	3390	2.95 "	"
79	"	2"	"	2000	128	.00270	1.785	.1172	.02836	.0138	2070	4.83 "	"
80	"	"	"	1850	107	.00211	"	.1170	.02836	.0138	2070	4.83 "	"
81	"	"	"	2175	86	.00242	"	.1170	.02836	.0138	2070	4.83 "	"
82	"	"	"	2070	64	.00189	"	.1170	.02836	.0138	2070	4.83 "	"
83	10.12	4	"	563	128	.00164	2.52	.1117	.02677	.0128	3150	3.18 "	"
84	"	2	"	825	128	.00212	2.12	.1129	.02838	.0135	2510	3.98 "	"
85	"	"	"	915	104	.00196	"	.1127	.02856	.0134	2530	3.95 "	"
86	"	"	"	915	80	.00218	"	.1130	.02838	.0135	2510	3.98 "	"
87	"	"	"	929	66.5	.00215	"	.1130	.02836	.0135	2510	3.98 "	"
88	5.06	4	"	2115	80	.00216	"	.1170	.02677	.0132	2570	3.89 "	"
89	"	"	"	1910	66.5	.00187	"	.1169	.02677	.0132	2570	3.89 "	"
90	"	"	"	1212	128	.00209	"	.1170	.02677	.0132	2570	3.89 "	"

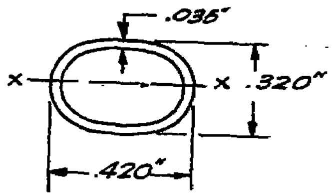
Note: Sheet thickness for all specimens = .010"

TABLE I (CONT'D)

Test	Long Spac- ing b	Frame Spac- ing d	Radius	Ultimate Applied Shear	Moment arm - to fixed end.	Strain at Failure	$\sqrt[4]{bd}$	P_x	P_y	$\sqrt[4]{P_x P_y^3}$	$\sqrt[4]{\frac{bd}{P_x P_y^3}}\,R$	$\sqrt[4]{\frac{P_x P_y^3}{bd}}\,\frac{1}{R}$	Type of Failure
91	5.06"	4"	16"	1331#	116"	.00194	2.12	.1169	.02677	.0132	2570	3.89x10-4	Gen. In- stability
92	"	8	"	503	194	.00152	2.52	.1167	.02335	.0119	3390	2.95 "	"
93	"	"	"	1353	74	.00135	"	.1166	"	.0119	3390	2.95 "	"
94	2.62	"	10"	960	114	.00174	-	-	-	-	-	- -	Panel in- stability
95	"	"	"	1283	88.4	.00290	2.14	.1165	.02335	.0119	1800	5.55 "	Gen. In- stability
96	"	"	"	1711	66	.00265	"	.1166	"	.0119	1800	5.55 "	"
97	"	"	"	2900	40.5	.00207	-	-	-	-	-	-	Shear
98	"	4	"	1310	113	.00340	1.80	.1165	.02677	.0132	1360	7.35 "	Gen. In- stability
99	"	"	"	1660	88.4	.00330	"	.1164	"	.0132	1360	7.35 "	"
100	"	"	"	2250	65	.00270	-	-	-	-	-	-	Bending- Shear
101	"	"	"	3300	40.5	.00260	-	-	-	-	-	-	Shear
102	2.53	2	16	2480	137	.00282	1.50	.1160	.02836	.0137	1750	5.71 "	Gen. In- stability
103	"	"	"	2860	112.4	.00277	"	.1160	"	.0137	1750	5.71 "	"
104	"	"	"	4200	89	.00343	"	.1157	"	.0137	1760	5.71 "	"
105	"	"	"	4500	65.1	.00218	-	-	-	-	-	-	Shear
106	2.62	"	10	1490	113	.00396	1.51	.1161	.02836	.0138	1090	9.17 "	Gen. In- stability
107	"	"	"	2760	65	.00450	"	.1160	"	.0137	1100	9.10 "	"
108	"	"	"	4270	40.5	.00398	"	.1161	"	.0138	1090	9.17 "	"
109	5.24	8	"	450	113	.00186	2.54	.1162	.02335	.0119	2130	4.69 "	"

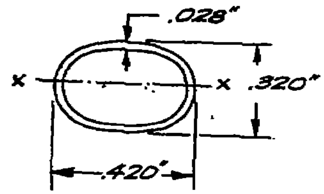
TABLE I (CONT'D)

Test	Long Spac-ing b	Frame Spac-ing d	Radius	Ultimate Applied Shear	Moment arm - to fixed end.	Strain at Failure	$\sqrt[4]{bd}$	ρ_x	ρ_y	$\sqrt[4]{(\rho_x\rho_y)^3}$	$\sqrt[4]{\frac{bd}{(\rho_x\rho_y)^3}}R$	$\sqrt[4]{\frac{(\rho_x\rho_y)^3}{bd}}R$	Type of Failure
110.	5.24"	8"	10"	1470	40.5	.00242	2.54	.1166	.02335	.0119	2130	4.69x10-4	Gen. Instability
111	"	4	"	660	113	.00251	2.14	.1170	.02677	.0132	1620	6.17 "	"
112	"	"	"	1760	40.5	.00290	"	.1169	"	.0132	1620	6.17 "	"
113	"	"	"	930	88.4	.00265	"	.1169	"	.0132	1620	6.17 "	"
114	2.53	"	16"	1900	137	.00216	1.785	.1162	"	.0132	2160	4.63 "	"
115	"	"	"	2010	112.4	.00194	"	.1163	"	.0132	2160	4.63 "	"
116	"	"	"	2400	89	.00217	"	.1162	"	.0132	2160	4.63 "	"
117	"	"	"	2450	65.3	.00136	-	-	-	-	-	-	Shear
118	5.24	2	10	710	113	.00380	1.80	.1170	.02836	.0138	1300	7.69 "	Gen. Instability
119	"	"	"	990	88.4	.00364	"	.1170	"	.0138	1300	7.69 "	"
120	"	"	"	1460	65	.00353	"	.1169	"	.0138	1300	7.69 "	"
121	"	"	"	2310	40.5	.00374	"	.1170	"	.0138	1300	7.69 "	"
122	2.62	1	"	1665	113	.00525	1.27	.1169	.02801	.0136	930	10.75 "	"
123	"	"	"	2140	88.4	.00492	"	.1160	"	.0136	930	10.75 "	"
124	"	"	"	3220	65	.00481	"	.1160	"	.0136	930	10.75 "	"
125	"	"	"	5280	40.5	.00479	"	.1160	"	.0136	930	10.75 "	"
126	5.08	4	16	1600	109	.00207	2.12	.1150	.02677	.0131	2590	3.86 "	"
127	"	"	"	1940	89	.00192	"	.1150	"	.0131	2590	3.86 "	"
128	"	"	"	1445	137	.00208	"	.1150	"	.0131	2590	3.86 "	"
129	"	"	"	2340	65	.00206	"	.1150	"	.0131	2590	3.86 "	"



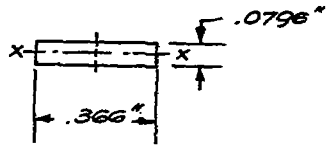
STIFFENER-S_2

AREA = .0368 I_{xx} = .000407



STIFFENER-S_1

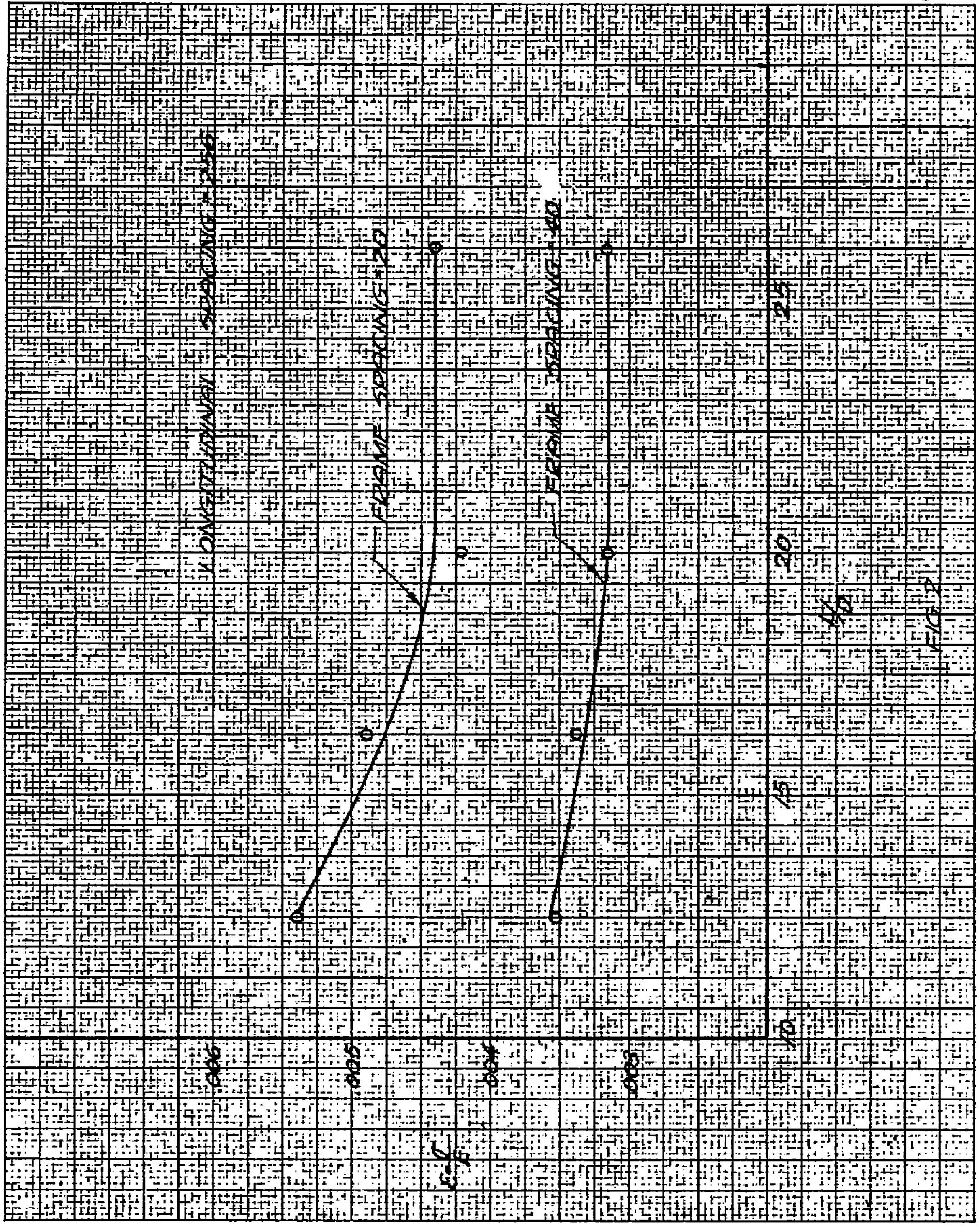
AREA = .0324 I_{xx} = .000374



FRAME-F_5

AREA = .0291 I_{xx} = 1.537×10^{-5}

FIG. 1


LONGITUDINAL SPACING
FRAME SPACING
FRAME SPACING
.006
.005
.004
.003
10
15
20
25

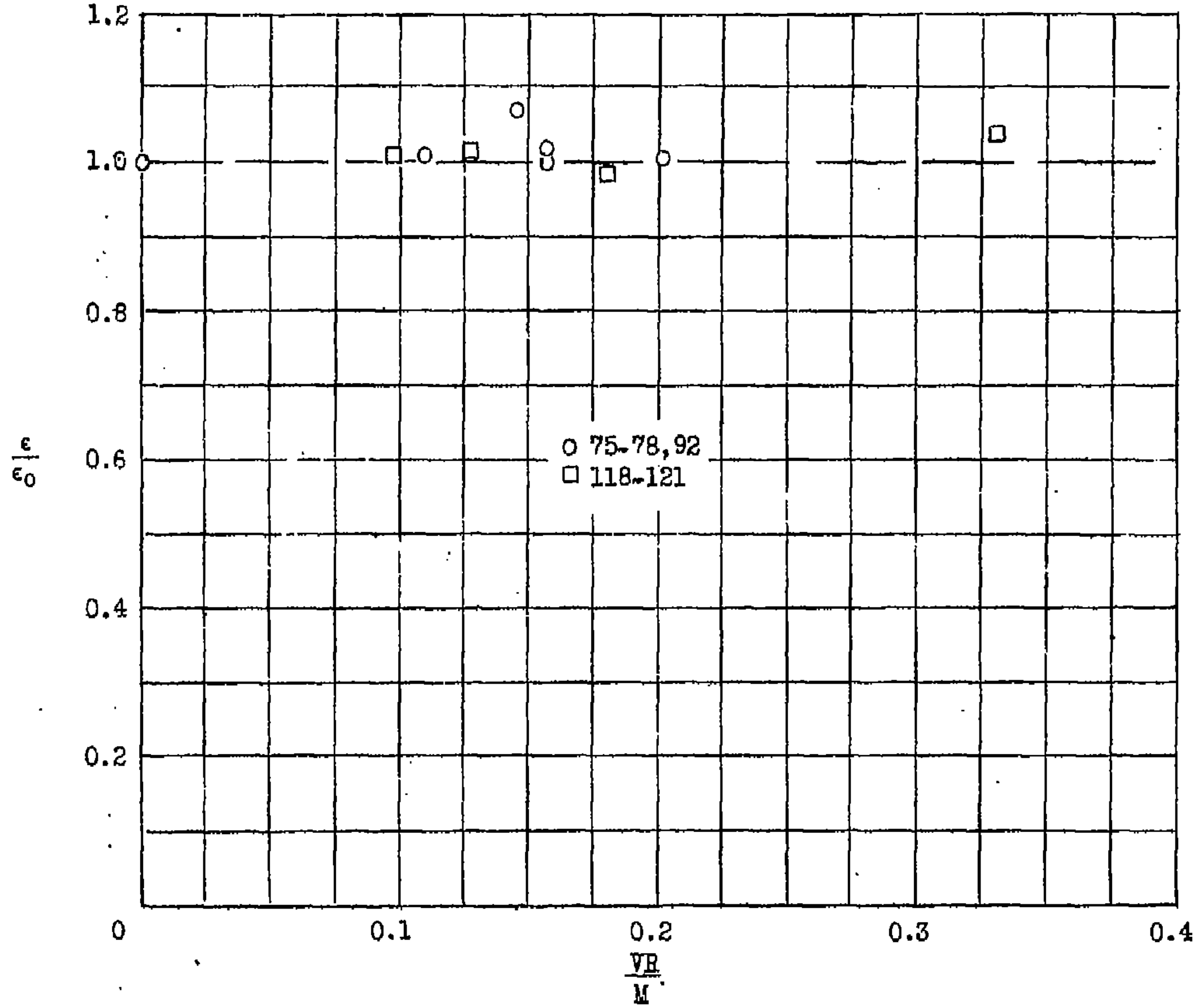

1.2
1.0
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
$\frac{\epsilon}{\epsilon_0}$
$\frac{VR}{M}$
○ 75-78,92
□ 118-121

Figure 3.

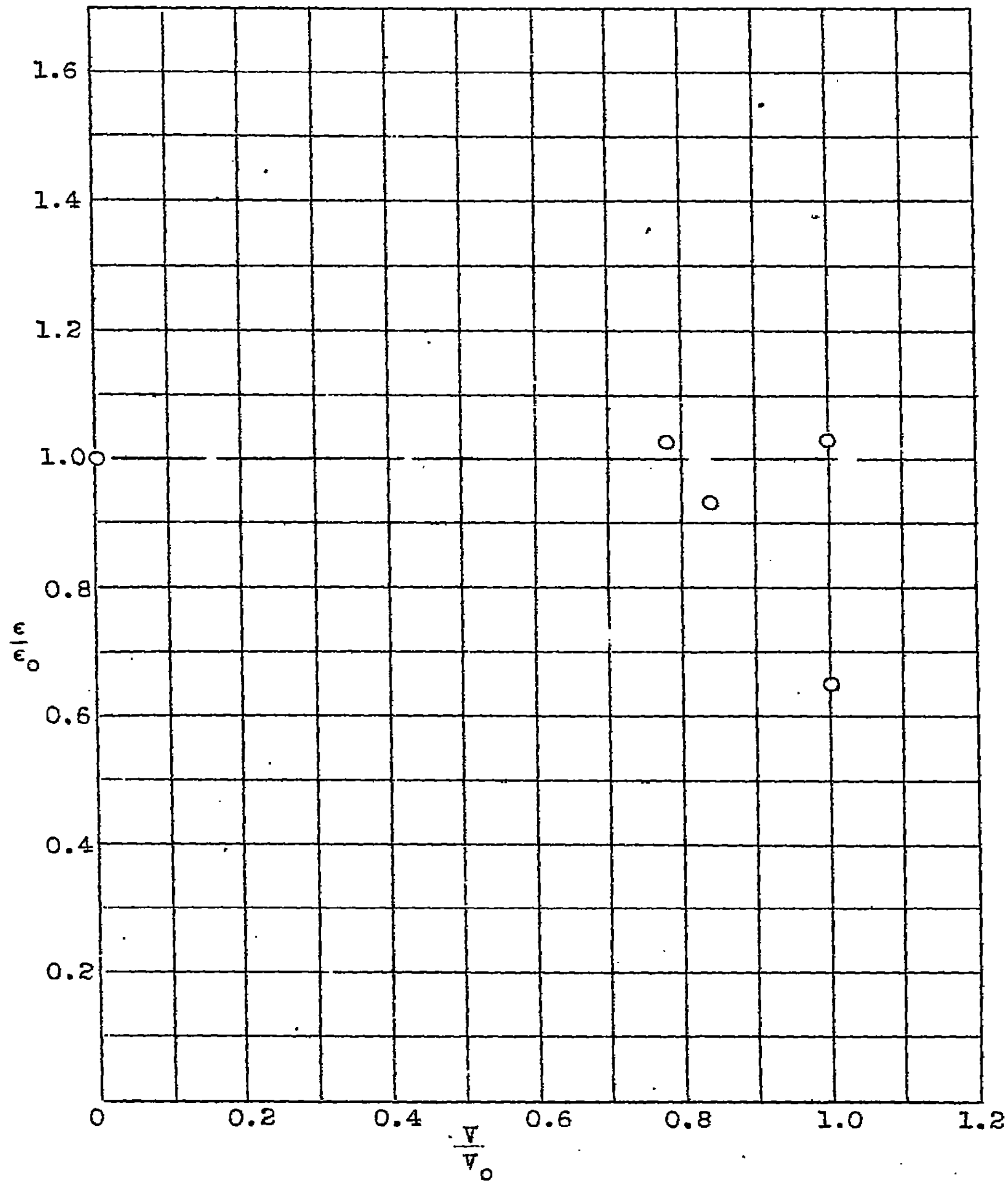

1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
$\frac{\epsilon}{\epsilon_o}$
0
0.2
0.4
0.6
0.8
1.0
1.2
$\frac{V}{V_o}$

Figure 4

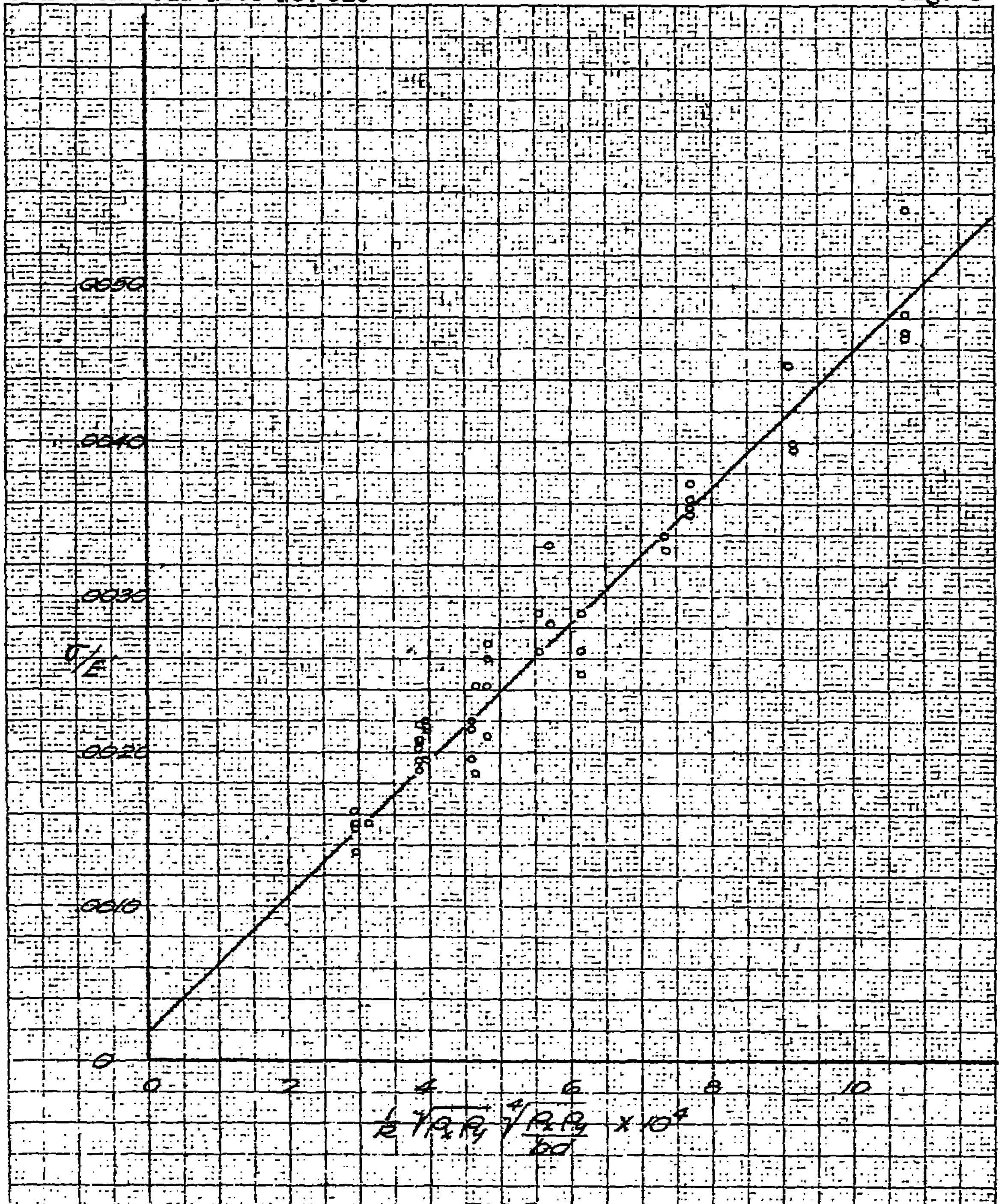


FIG 5

METHOD OF NUMBERING STIFFENERS

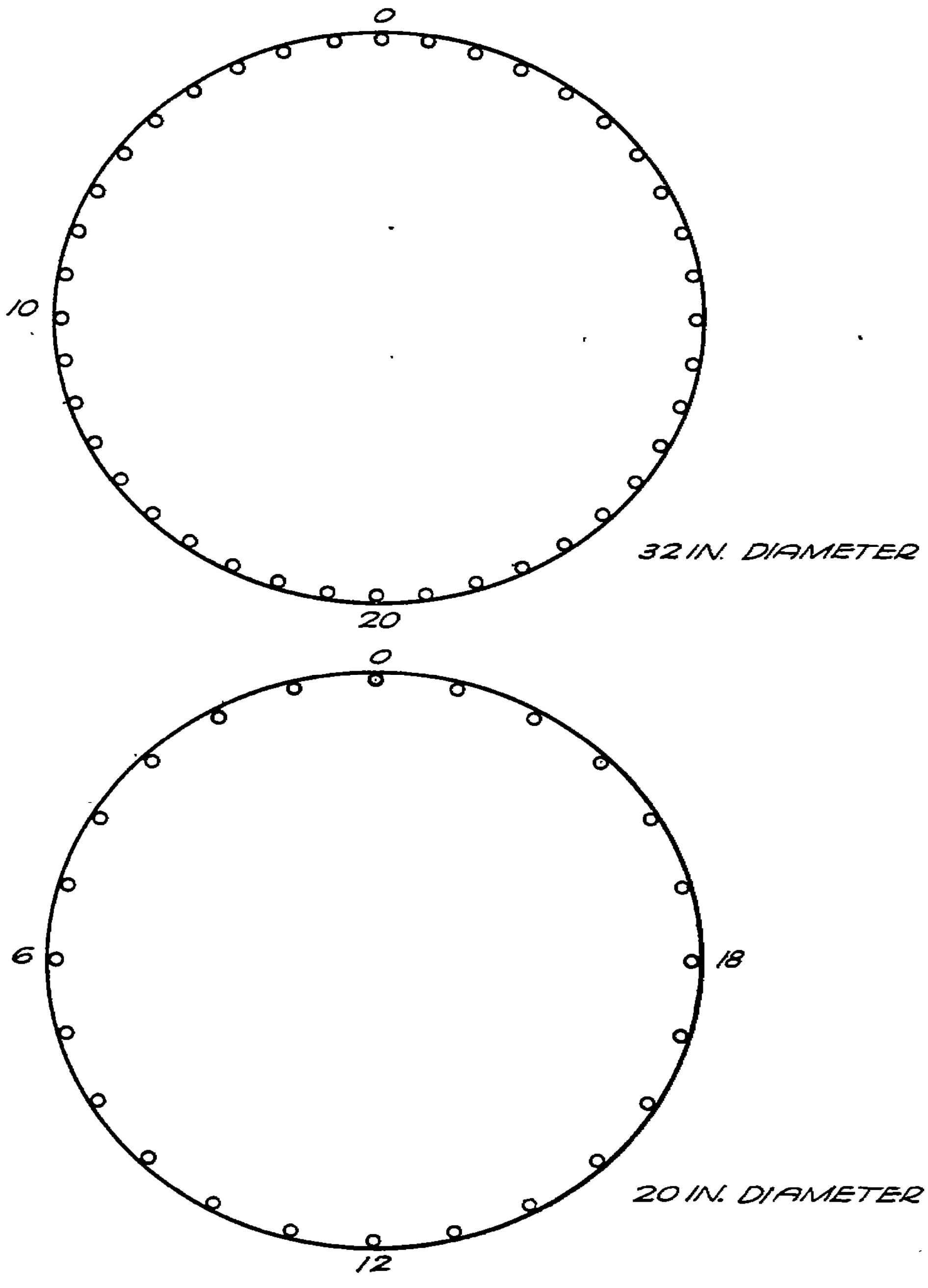


FIG 6

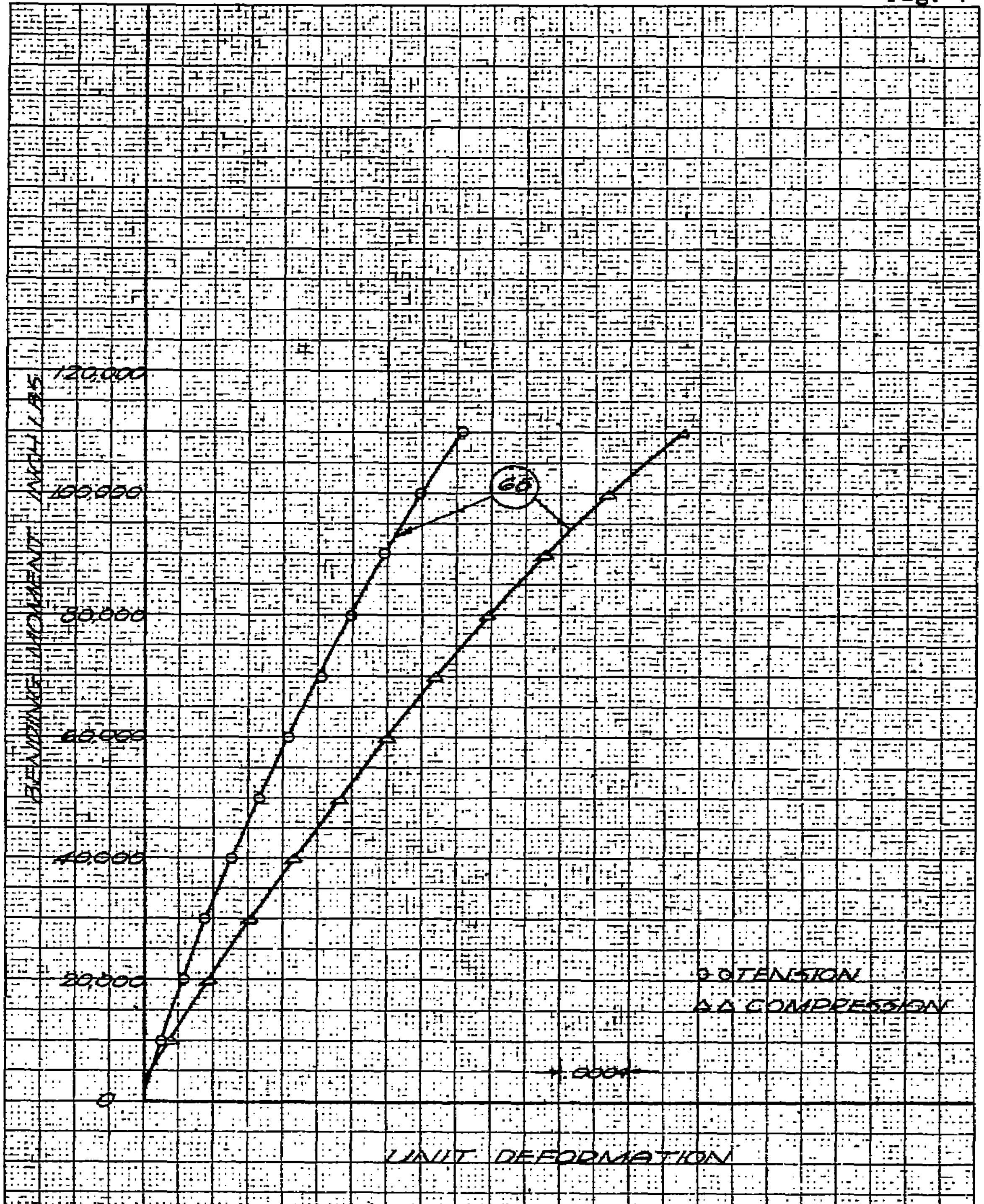
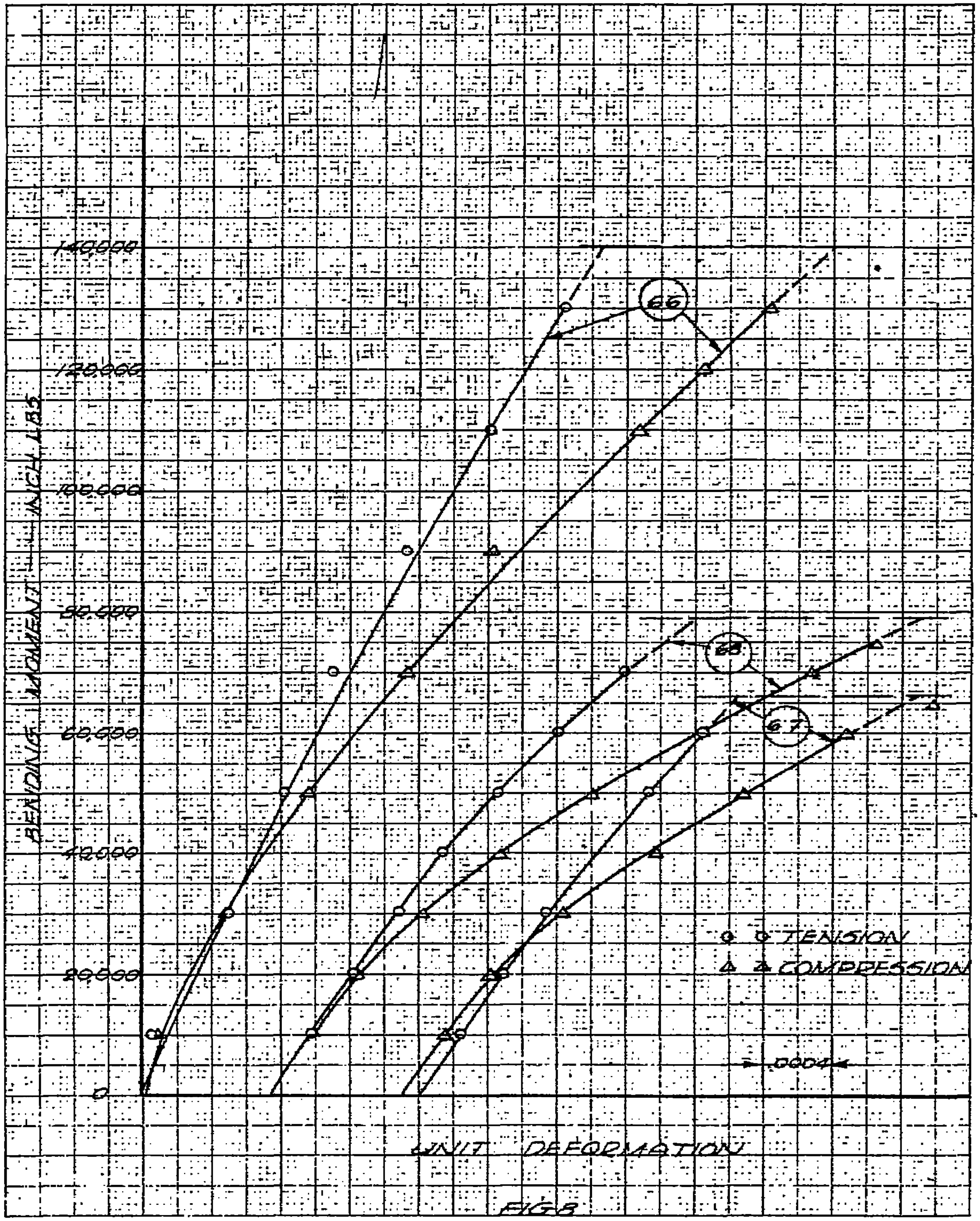

BENDING MOMENT INCH LBS
120,000
100,000
80,000
60,000
40,000
20,000
0
65
○ ○ TENSION
Δ Δ COMPRESSION
.0001
UNIT DEFORMATION

FIG 7



140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
BENDING MOMENT — INCH LBS
66
68
67
○ TENSION
△ COMPRESSION
.0004
UNIT DEFORMATION

FIG 8

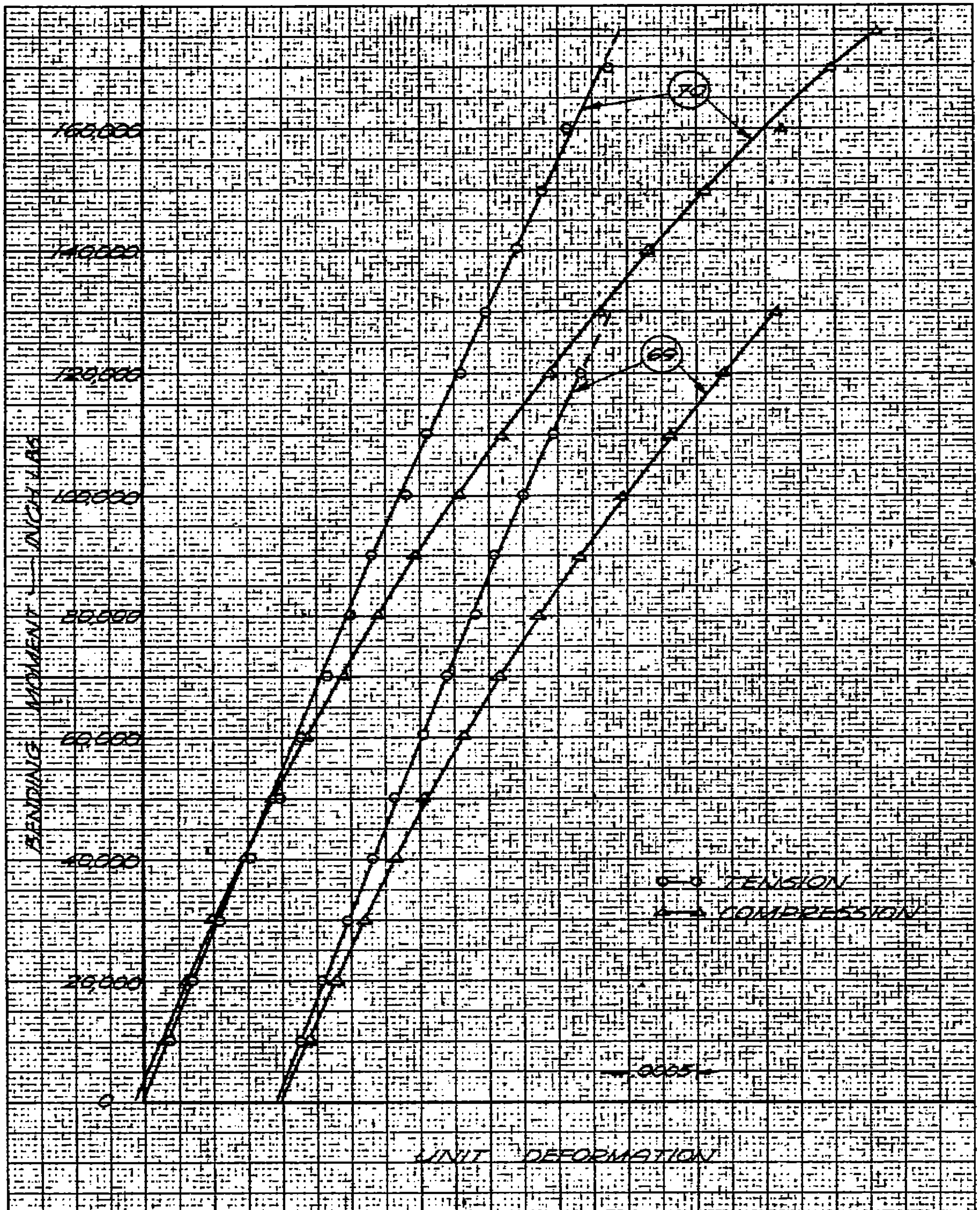

160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
BENDING MOMENT — INCH LBS
70
69
TENSION
COMPRESSION
.0005
UNIT DEFORMATION

FIG. 9

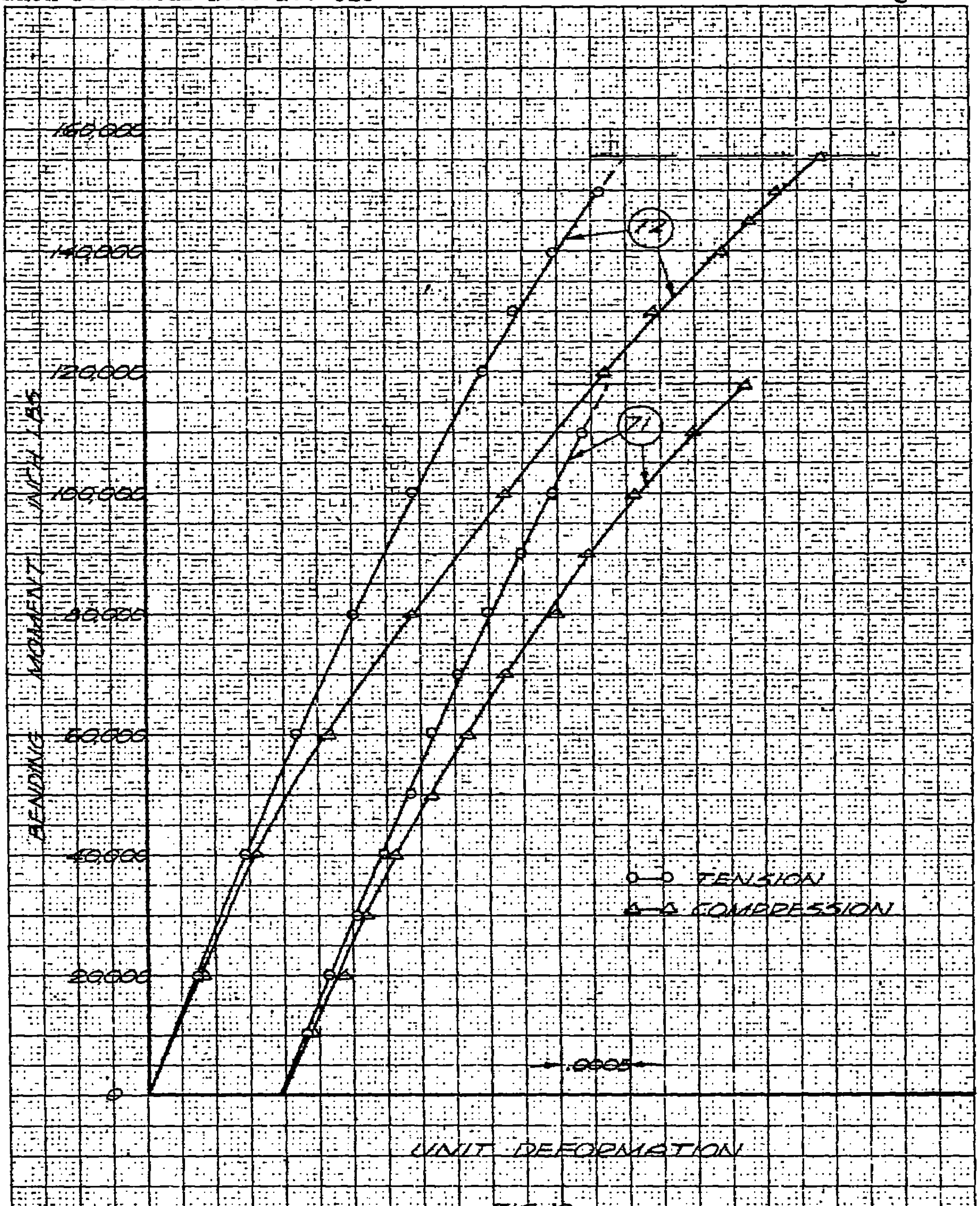
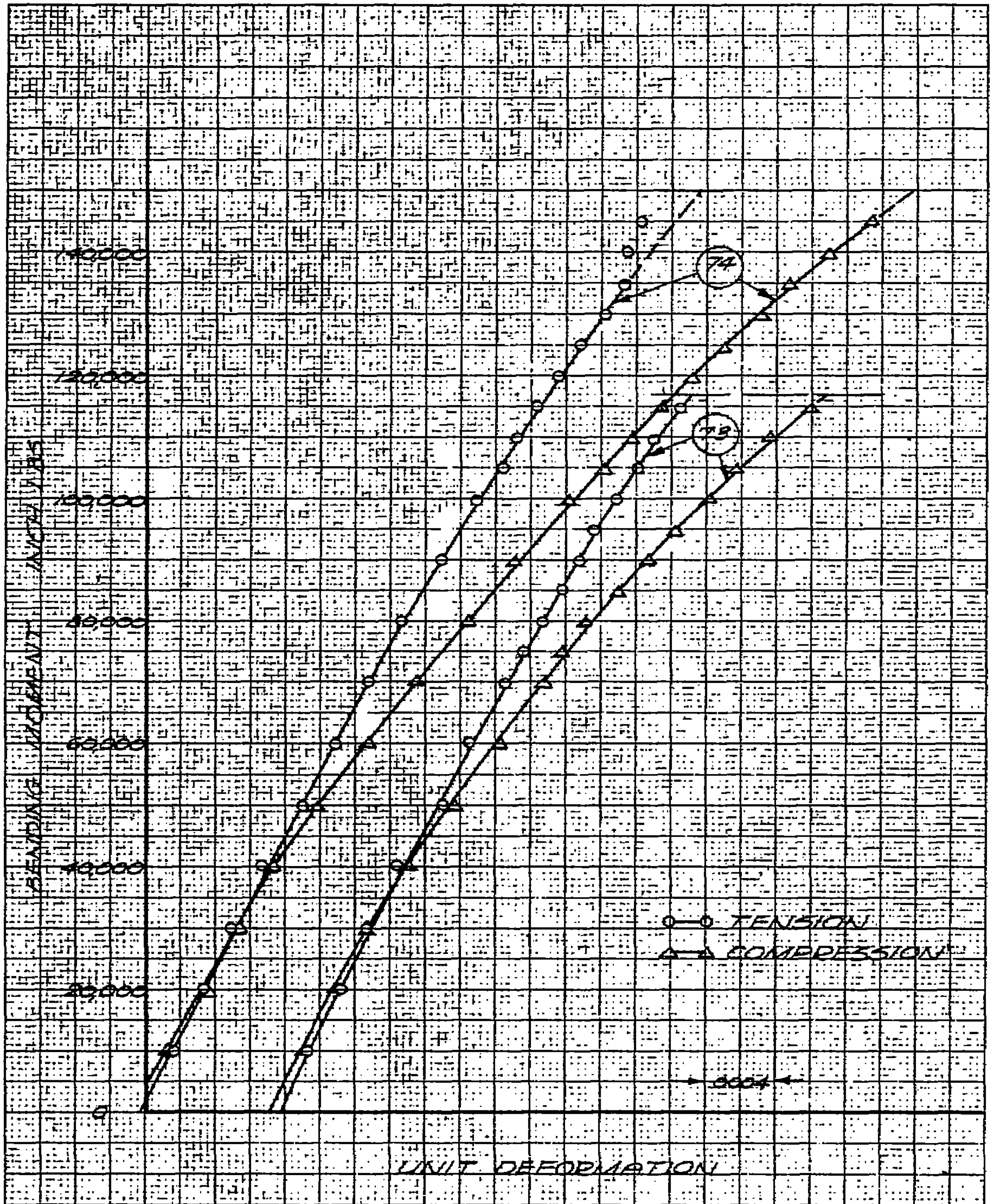

160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
BENDING MOMENT INCH LBS
72
71
TENSION
COMPRESSION
.0005
UNIT DEFORMATION

FIG 10



BENDING MOMENT INCH LBS
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
74
73
TENSION
COMPRESSION
.0004
UNIT DEFORMATION

FIG. 11

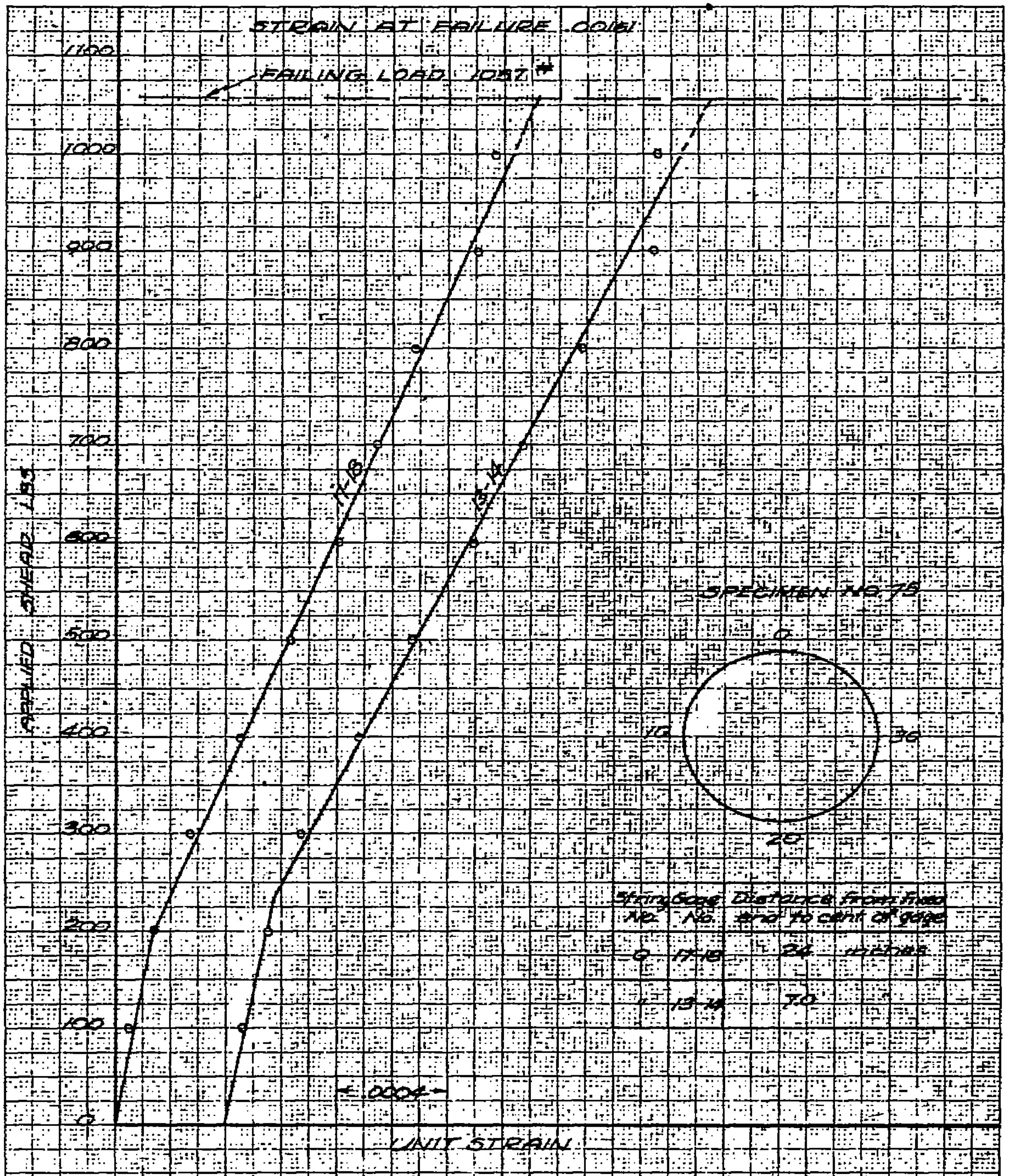
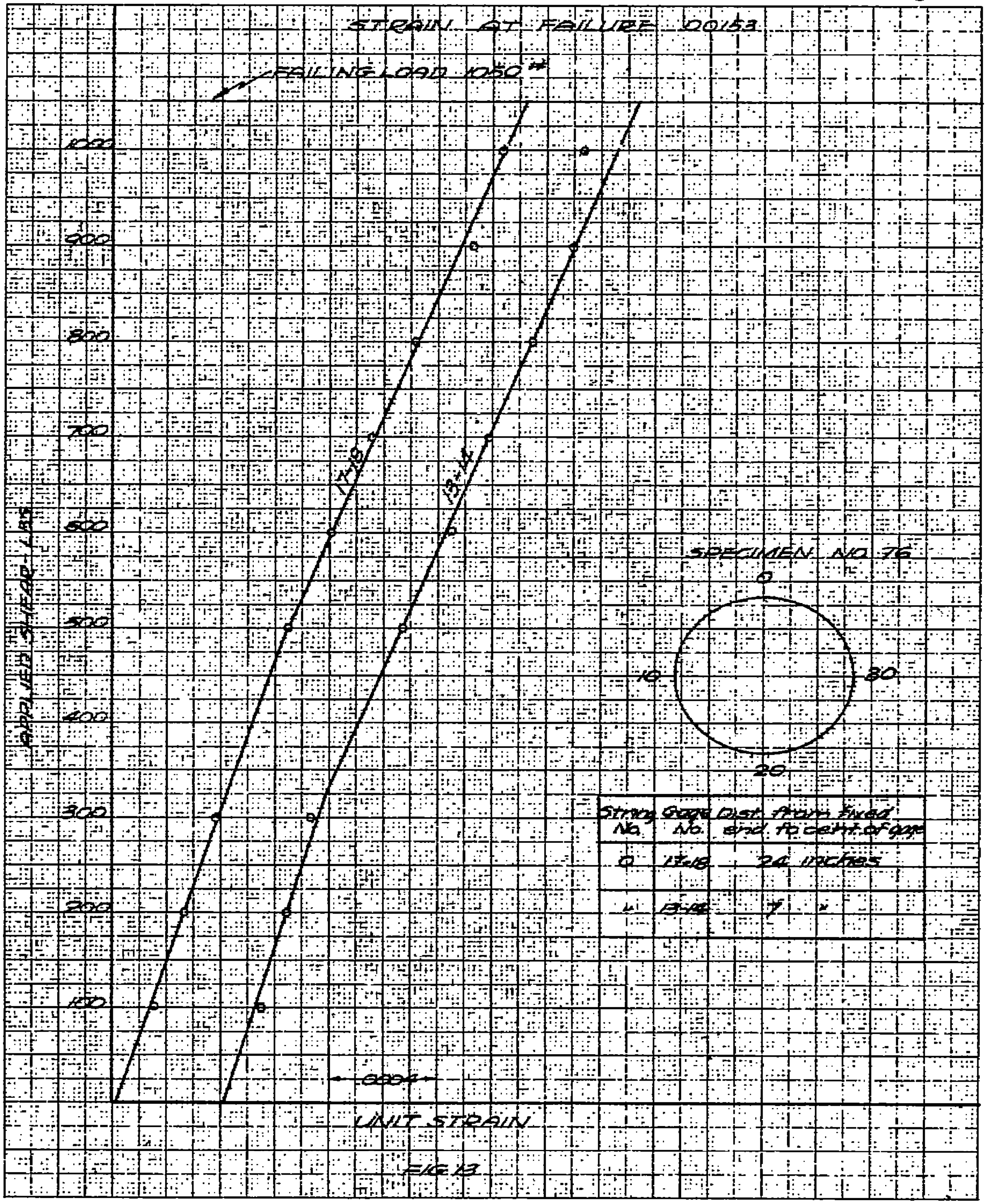

STRAIN AT FAILURE .00181
FAILING LOAD 1057 #
1100
1000
900
800
700
600
500
400
300
200
100
0
APPLIED SHEAR LBS
17-18
13-14
SPECIMEN NO. 75
0
10
30
20
String Gage Distance from fixed
No. No. end to cent. of gage
o 17-18 24 inches
13-14 7.0
.0004
UNIT STRAIN

FIG. 12


STRAIN AT FAILURE .00153
FAILING LOAD 1050 #
APPLIED SHEAR LBS
1000
900
800
700
600
500
400
300
200
100
17-18
13-14
SPECIMEN NO 76
0
10
20
30
String Gage Dist. from fixed
No. No. end to cent. of gage
o 17-18 24 inches
• 13-14 7 "
.0004
UNIT STRAIN
FIG 13

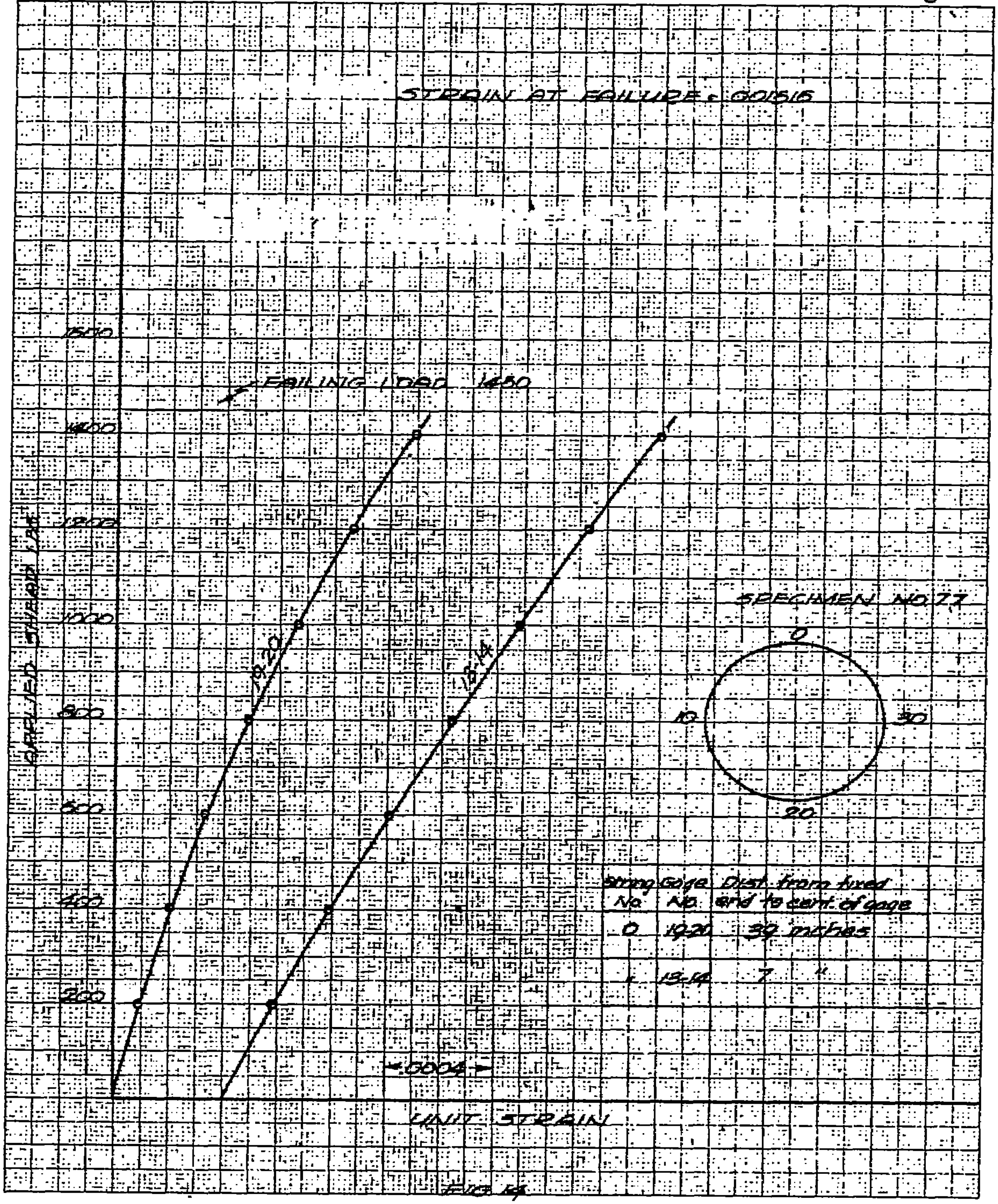

STRAIN AT FAILURE = .001516
FAILING LOAD 1450
1600
1400
1200
1000
800
600
400
200
APPLIED THREAD, LB
19.20
18.14
SPECIMEN NO 7.7
0
10
30
20
String Gage Dist. from fixed
No. No. end to cent. of gage
0 19.20 39 inches
" 18.14 7 "
.0004
UNIT STRAIN

FIG. 14

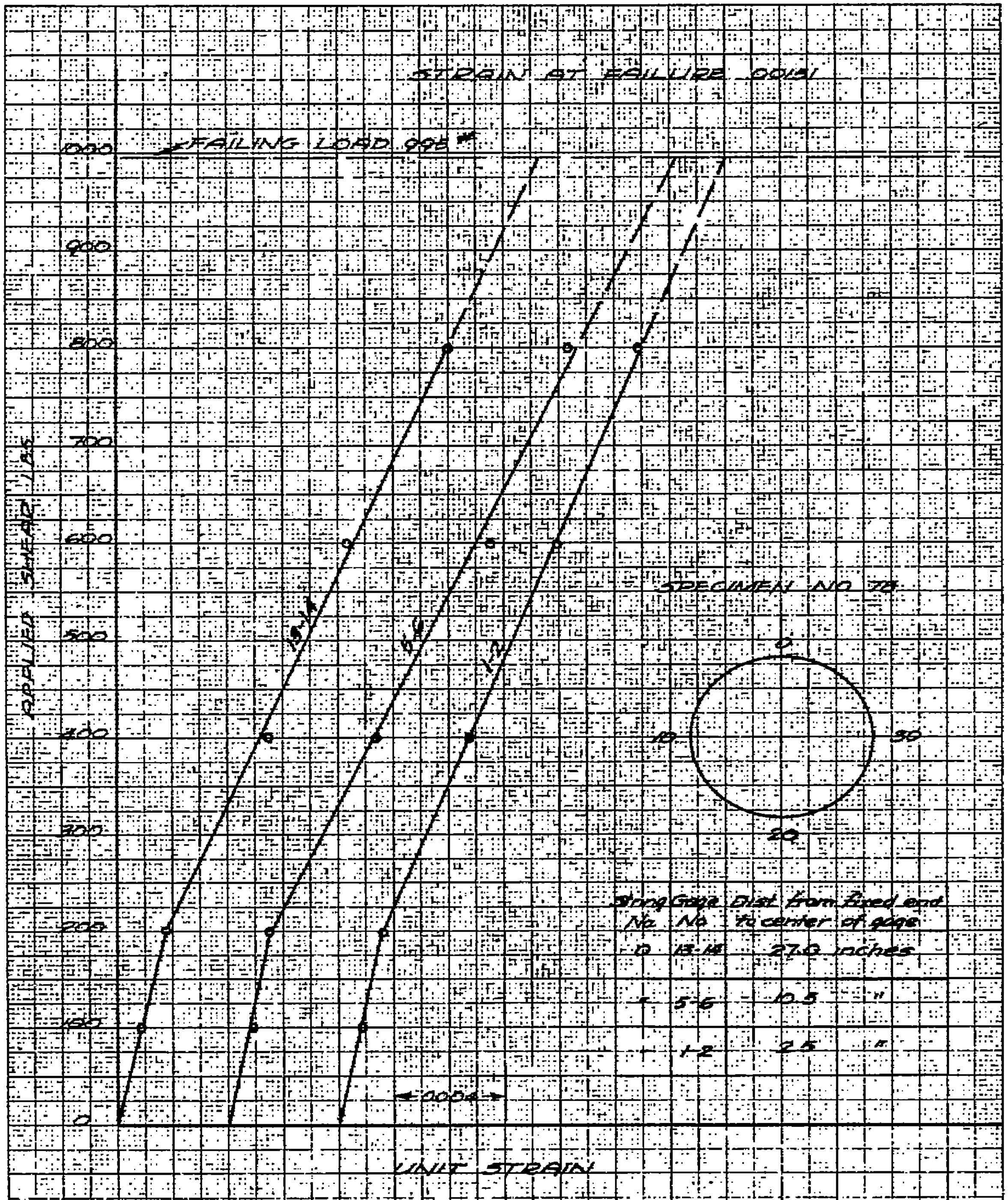
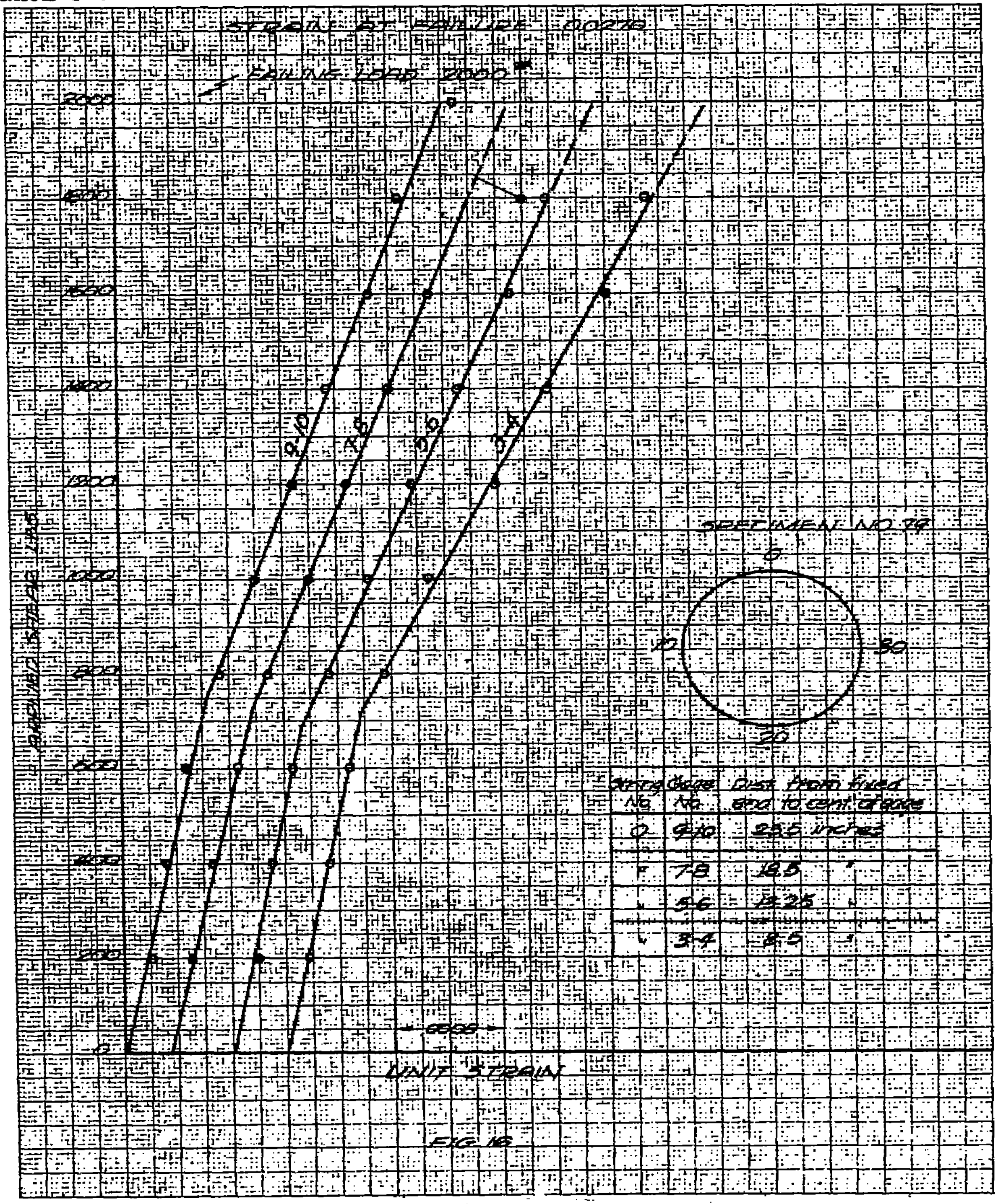
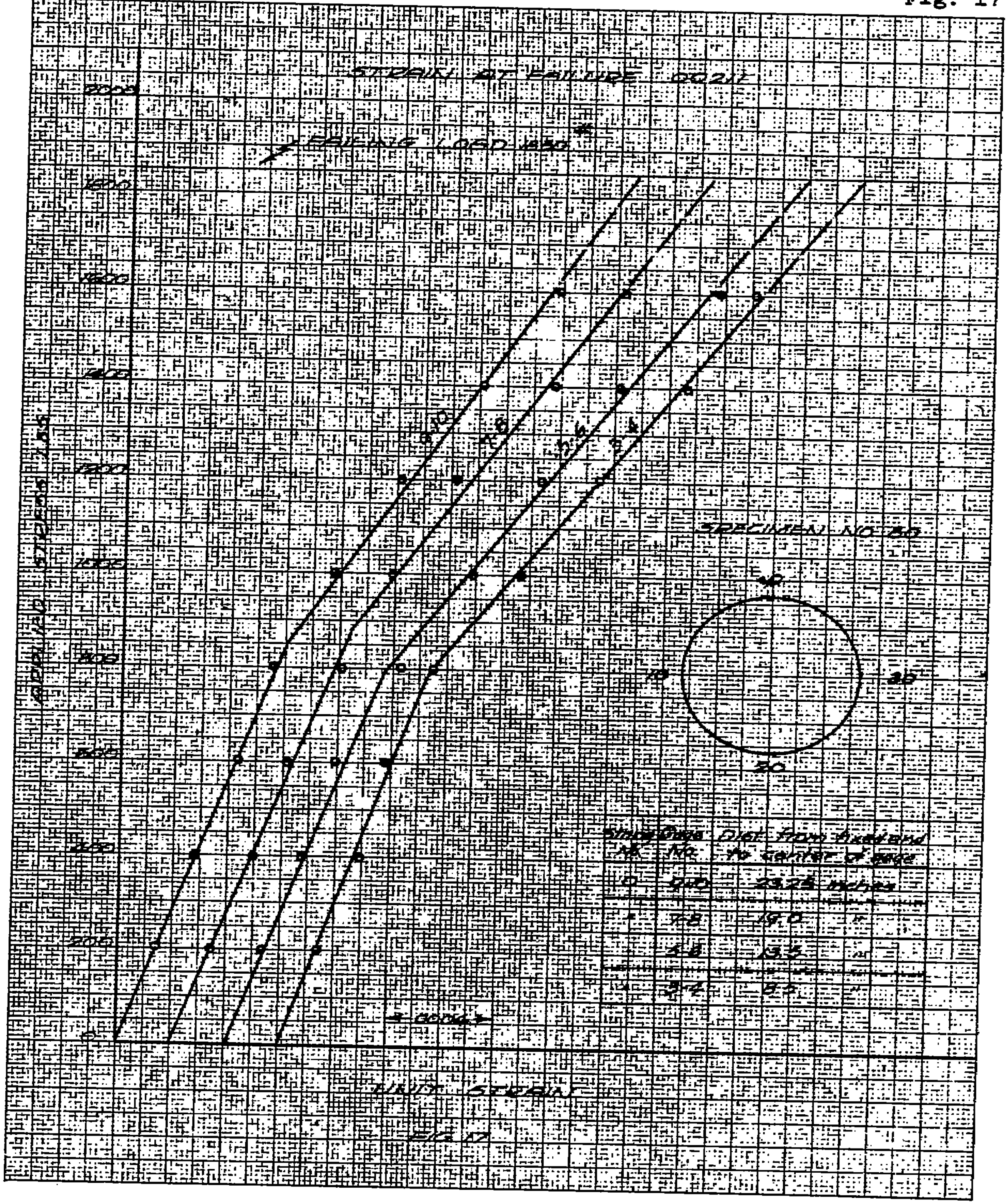
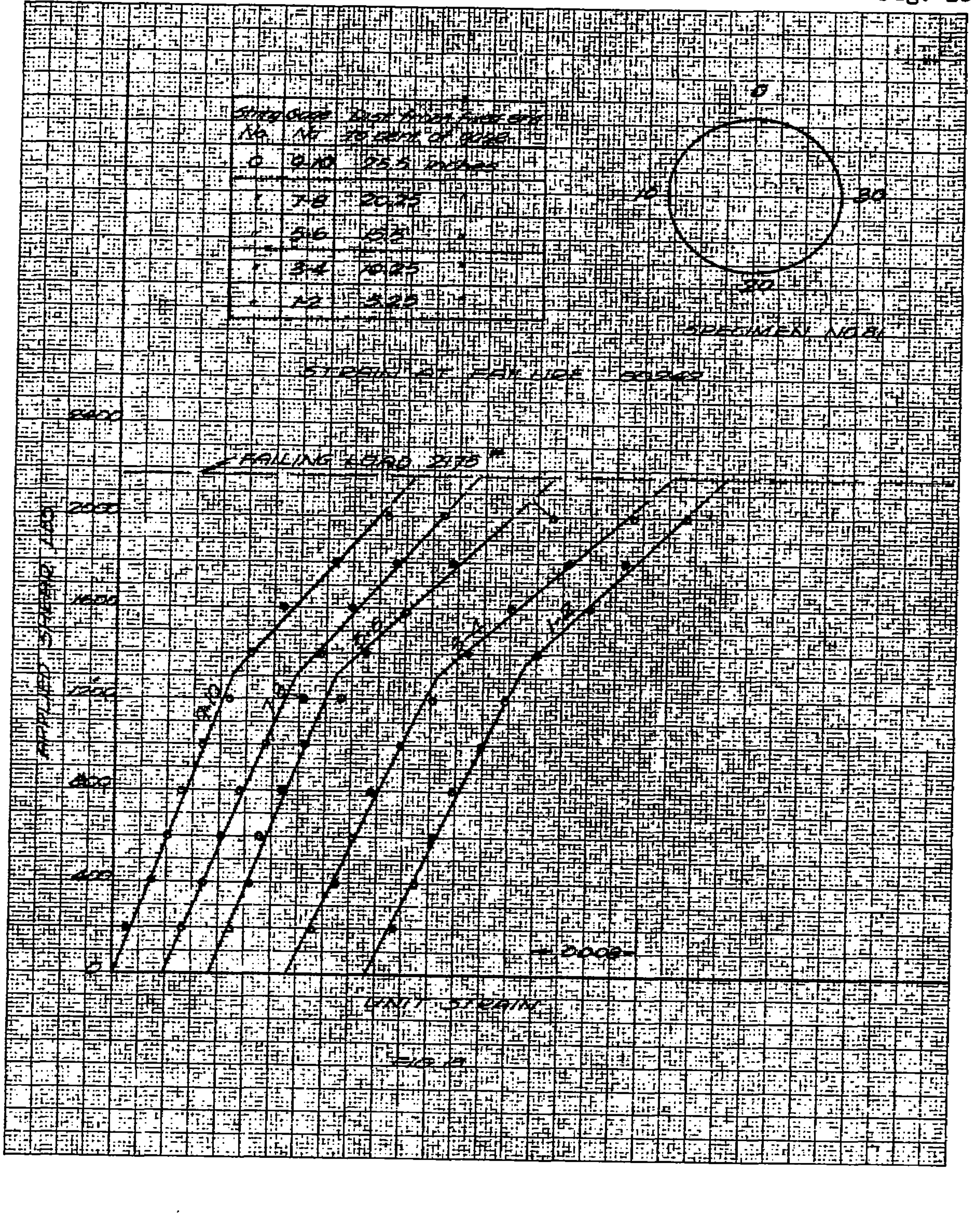
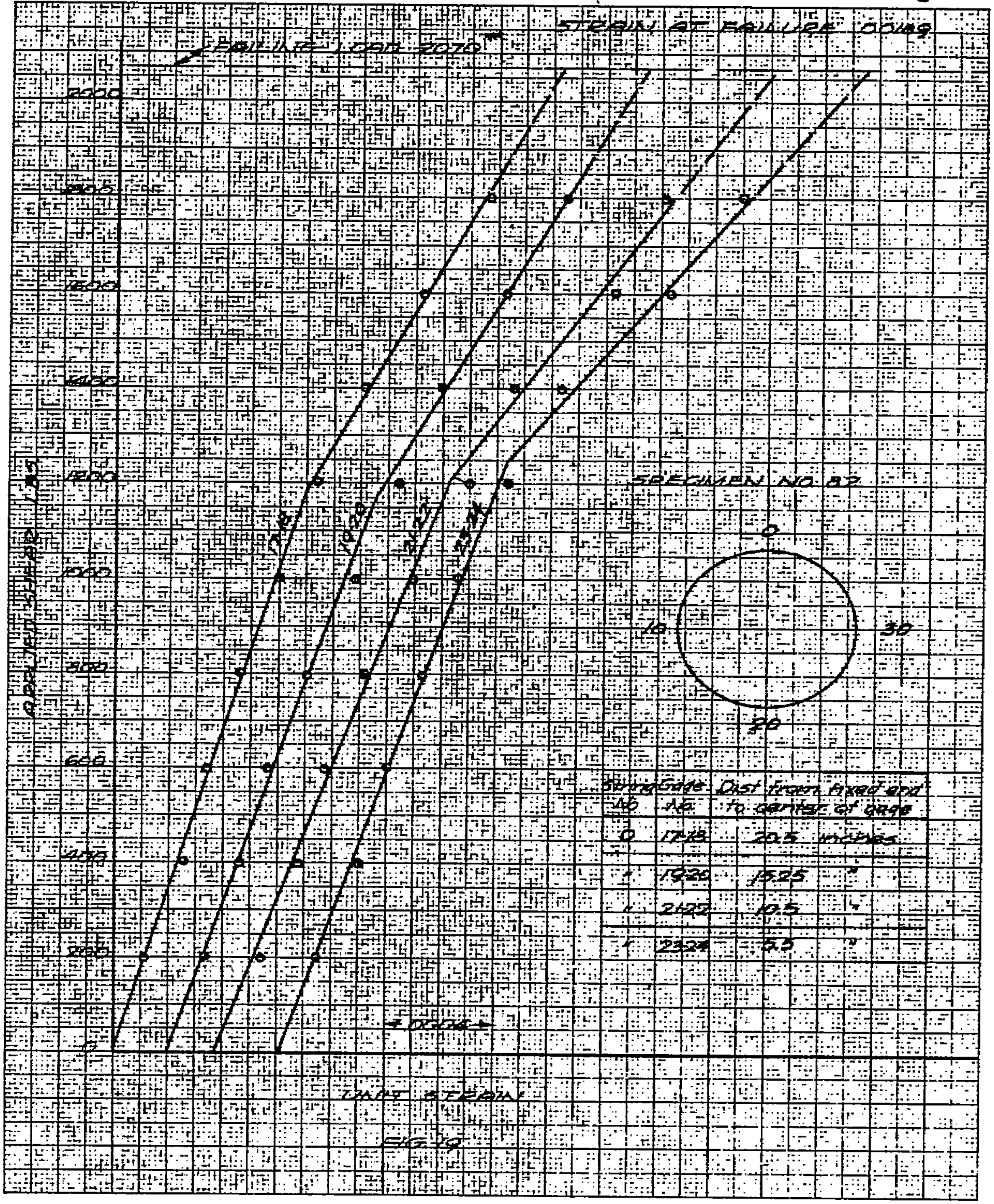

STRAIN AT FAILURE .00151
FAILING LOAD 995#
1000
900
800
700
600
500
400
300
200
100
0
APPLIED SHEAR LBS
13-14
5-6
1-2
SPECIMEN NO 7B
0
10
30
20
String Gage Dist from fixed end
No. No. to center of gage
13-14 27.0 inches
5-6 10.5 "
1-2 2.5 "
.0004
UNIT STRAIN

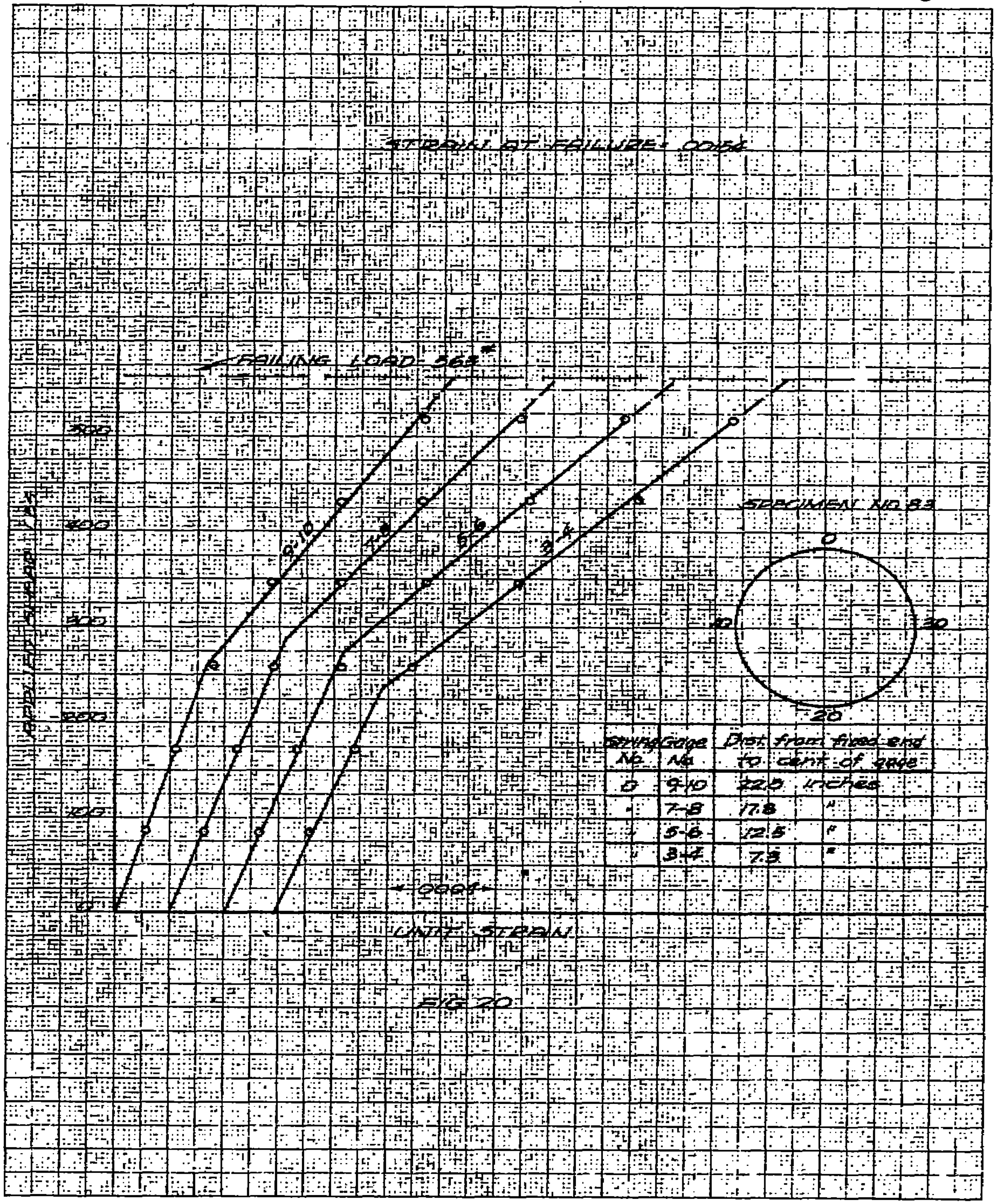
FIG 15

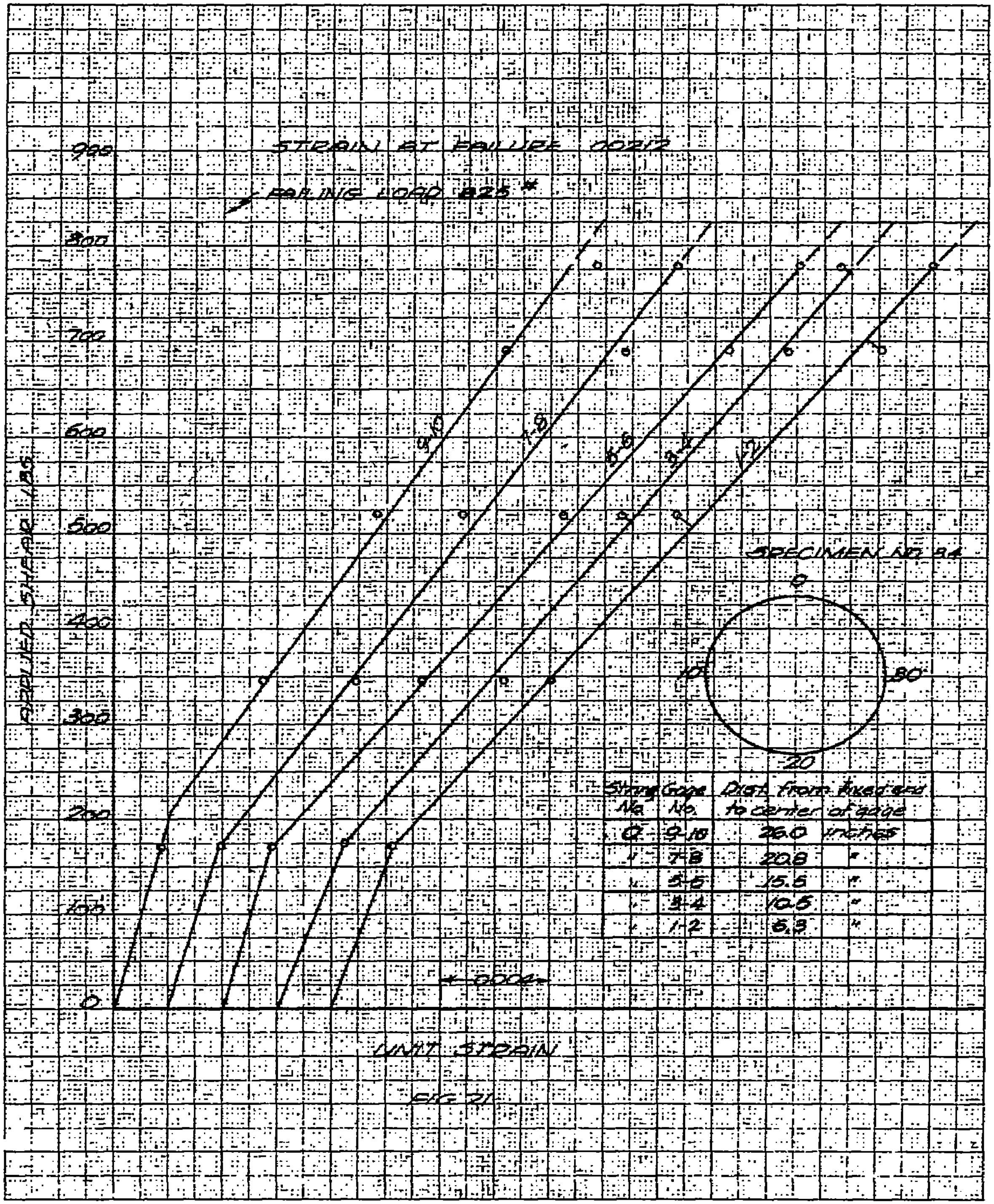

FAILING LOAD 2000#
2000
1600
1400
1200
1000
800
600
400
200
0
UNIT STRAIN
20
30
String No.
Gage No.
Dist. from fixed end to cent. of gage
9-10
23.5 inches
7-8
18.5
5-6
13.25
3-4
8.5
FIG 16

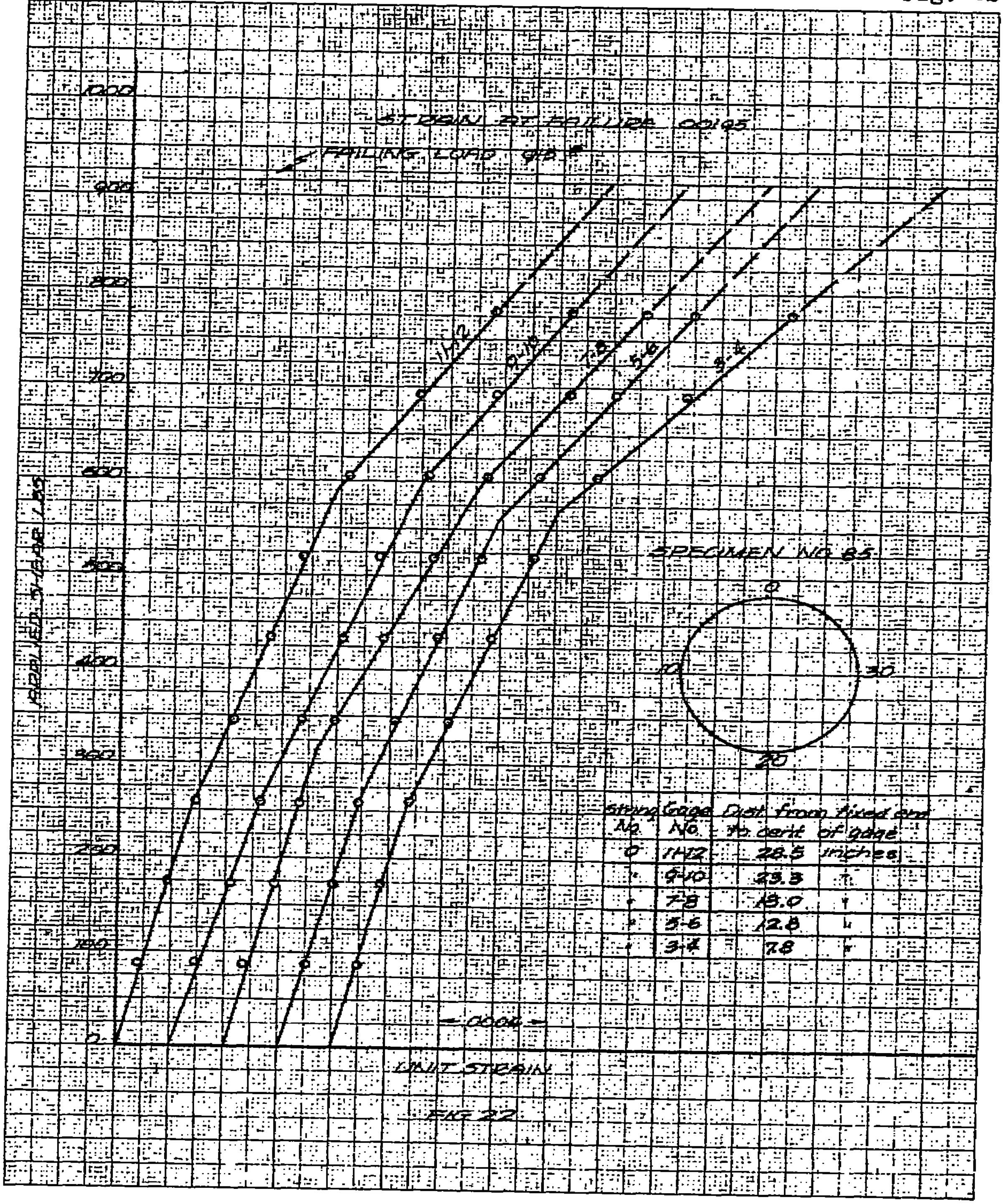

UNIT STRAIN
FIG. 17

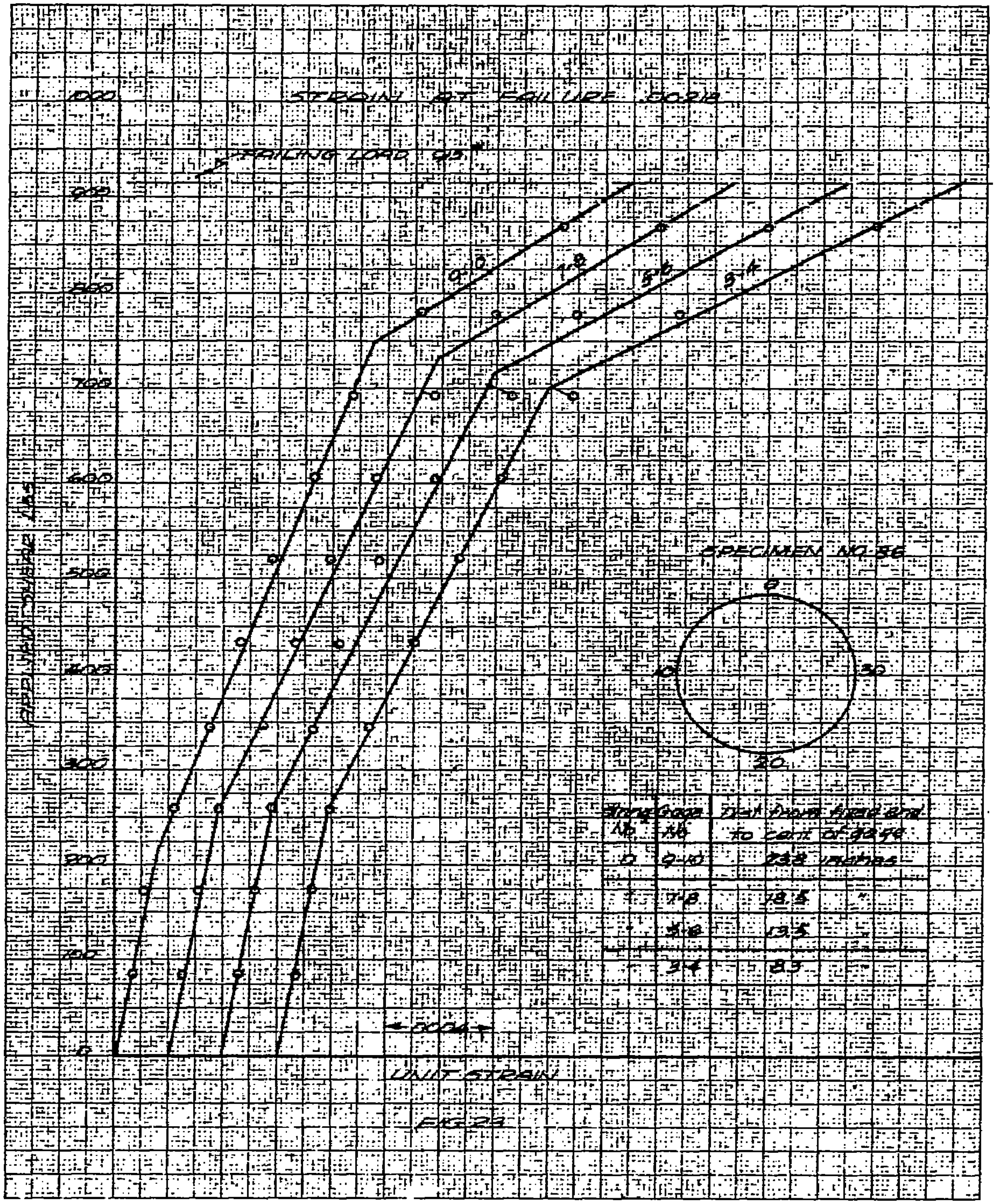

0
10
20
30
7-8
20.25
5-6
15.25
3-4
10.25
1-2
5.25
2400
FAILING LOAD 2175
2000
1600
1200
800
400
0
.0008
UNIT STRAIN


STRAIN AT FAILURE .00149
FAILURE LOAD 2070
SPECIMEN NO. 87
0
10
20
30
String Gage No. | Gage No. | Dist. from fixed end to center of gage
0 | 1718 | 20.5 inches
1 | 1920 | 15.25 "
" | 2122 | 10.5 "
" | 2324 | 5.5 "
UNIT STRAIN
APPLIED LOAD LBS
FIG. 19


SPECIMEN NO 83
String No.
Gage No.
Dist. from fixed end to cent. of gage
9-10
22.5 inches
7-8
17.8
5-6
12.5
3-4
7.3
UNIT STRAIN
FIG 20


STRAIN AT FAILURE .00212
FAILING LOAD 825 #
900
800
700
600
500
400
300
200
100
0
APPLIED SHEAR LBS
9-10
7-8
5-6
3-4
1-2
SPECIMEN NO 34
0
10
80
20
String No.
Gage No.
Dist. from fixed end to center of gage
0
9-10
26.0 inches
7-8
20.8
5-6
15.5
3-4
10.5
1-2
5.3
.0004
UNIT STRAIN
FIG 21


STRAIN AT FAILURE .00195
FAILING LOAD 918 #
1000
900
800
700
600
500
400
300
200
100
0
11-12
9-10
7-8
5-6
3-4
APPLIED SHEAR LBS
SPECIMEN NO 85
0
10
30
20
String Gage Dist. from fixed end
No. No. to cent of gage
0 11-12 28.5 inches
9-10 23.3
7-8 18.0
5-6 12.8
3-4 7.8
.0004
UNIT STRAIN
FIG 22


SPECIMEN NO. 36
10
20
30
UNIT STRAIN
1000
900
800
700
600
500
400
300
200
100
0

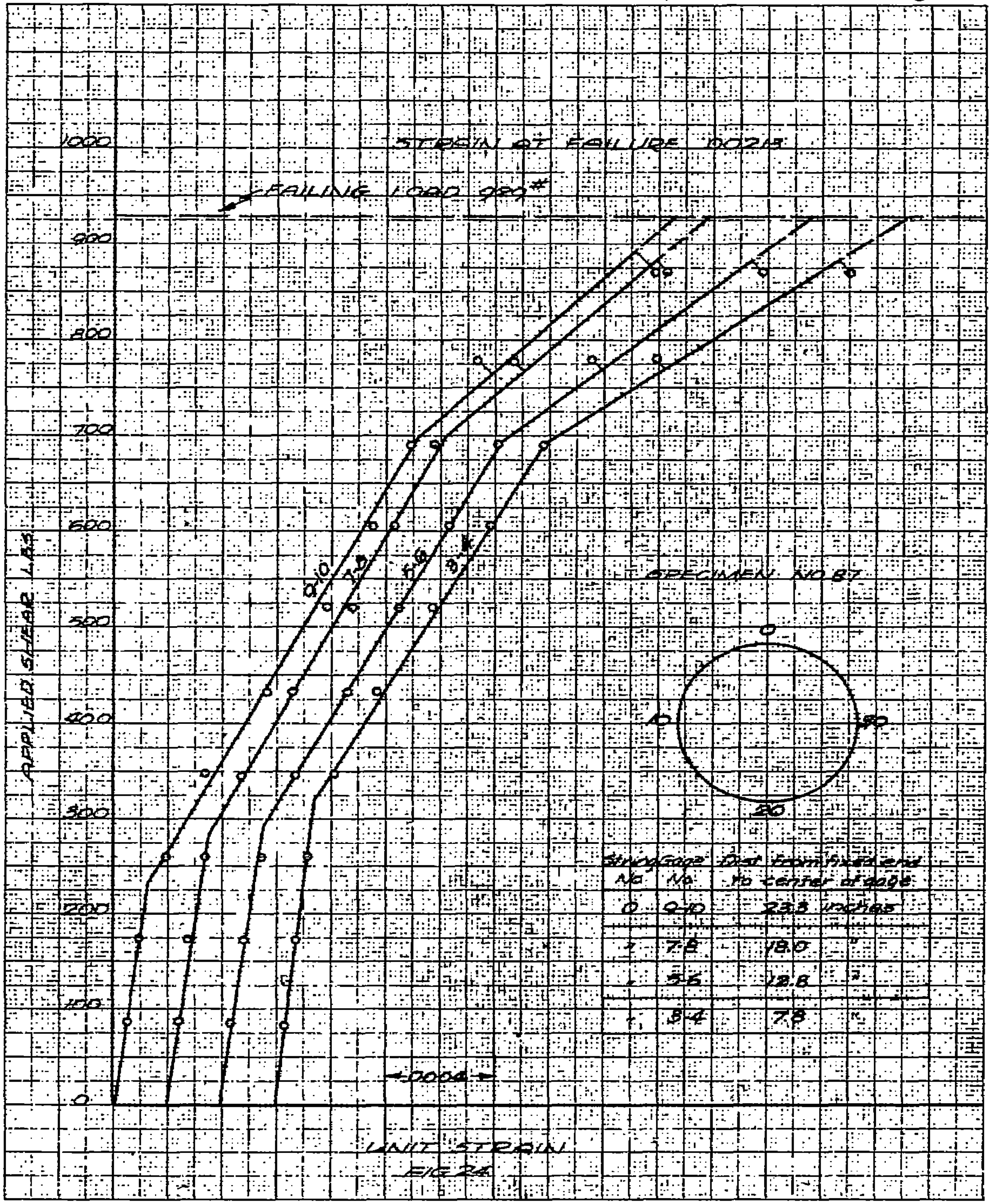
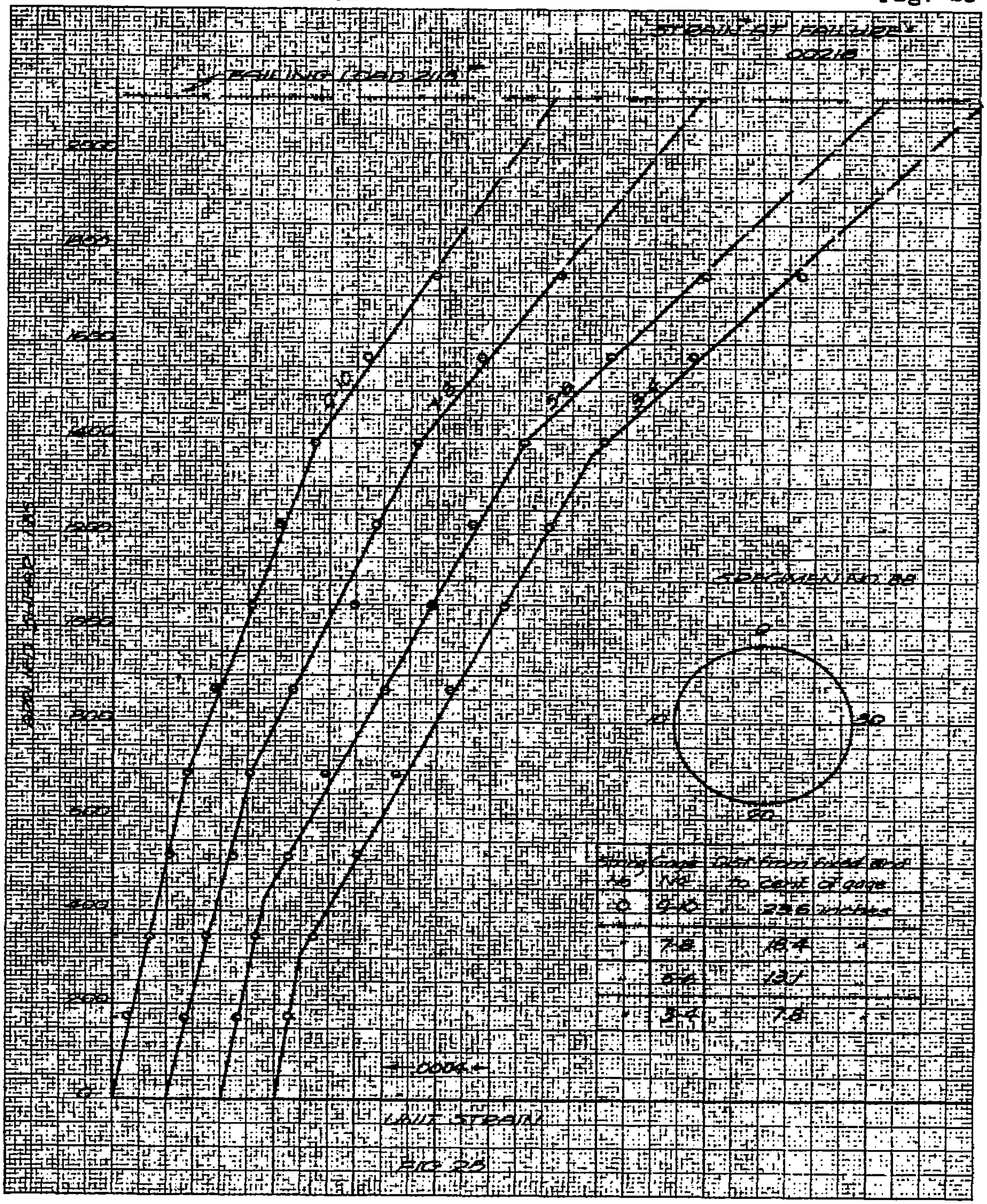
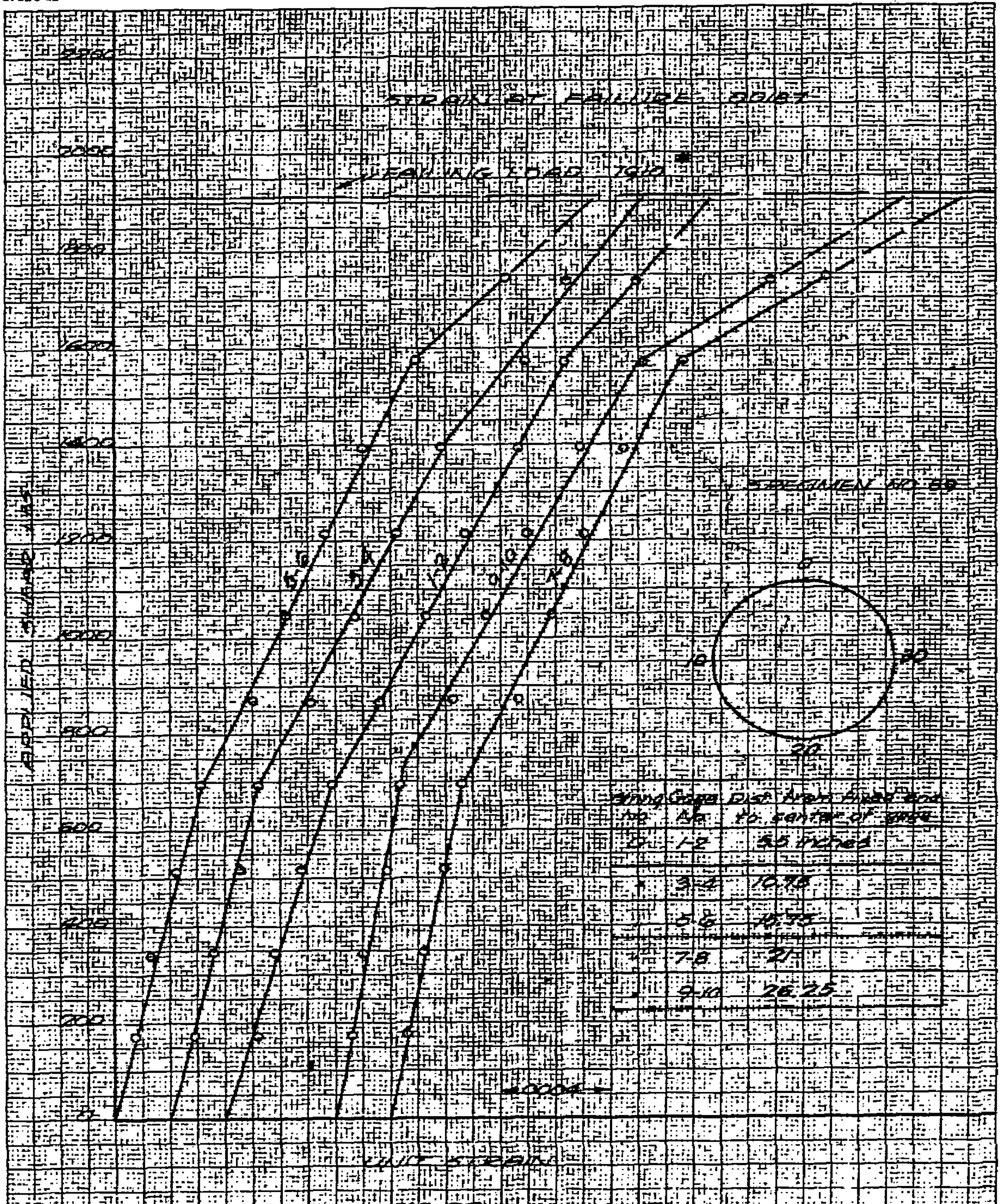

STRAIN AT FAILURE .00213
FAILING LOAD 980#
APPLIED SHEAR LBS.
1000
900
800
700
600
500
400
300
200
100
0
SPECIMEN NO 87
0
10
30
20
Strain Gage No. | Gage No. | Dist. from fixed end to center of gage
0 | 9-10 | 23.3 inches
1 | 7-8 | 18.0
2 | 5-6 | 12.8
3 | 3-4 | 7.8
.0004
UNIT STRAIN

FIG 24


FAILING LOAD 2113
STRAIN AT FAILURE
.00218
SPECIMEN NO. 38
UNIT STRAIN
.0004
FIG. 25


STRAIN AT FAILURE .00167
FAILING LOAD 1910
SPECIMEN NO 59
APPLIED SHEAR LBS.
UNIT STRAIN
.0004
Wing Gage No. | Gage No. | Dist from fixed end to center of gage
1-2 | 5.5 inches
3-4 | 10.75
5-6 | 15.75
7-8 | 21
9-10 | 26.25
10
20
30
FIG 26

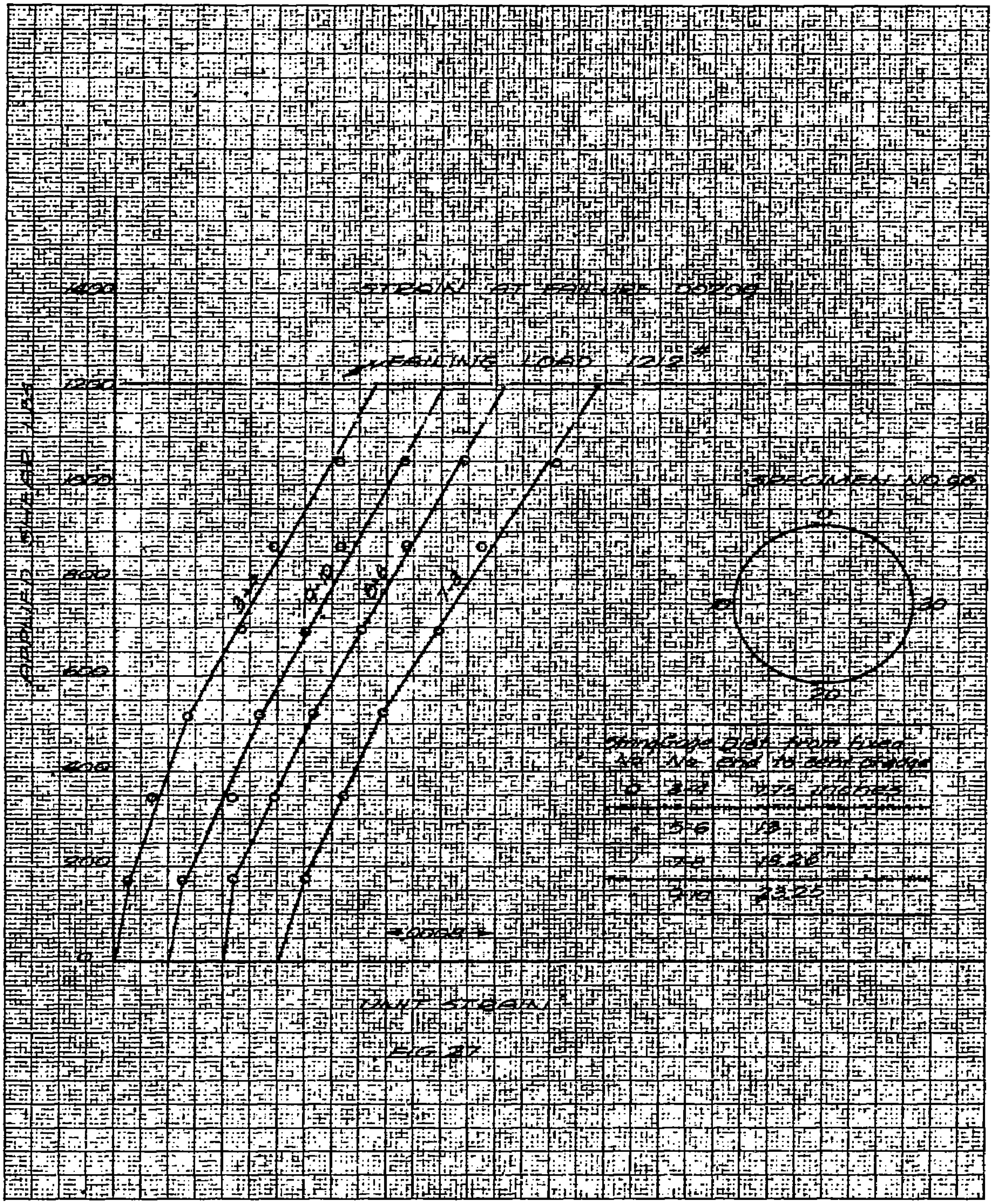
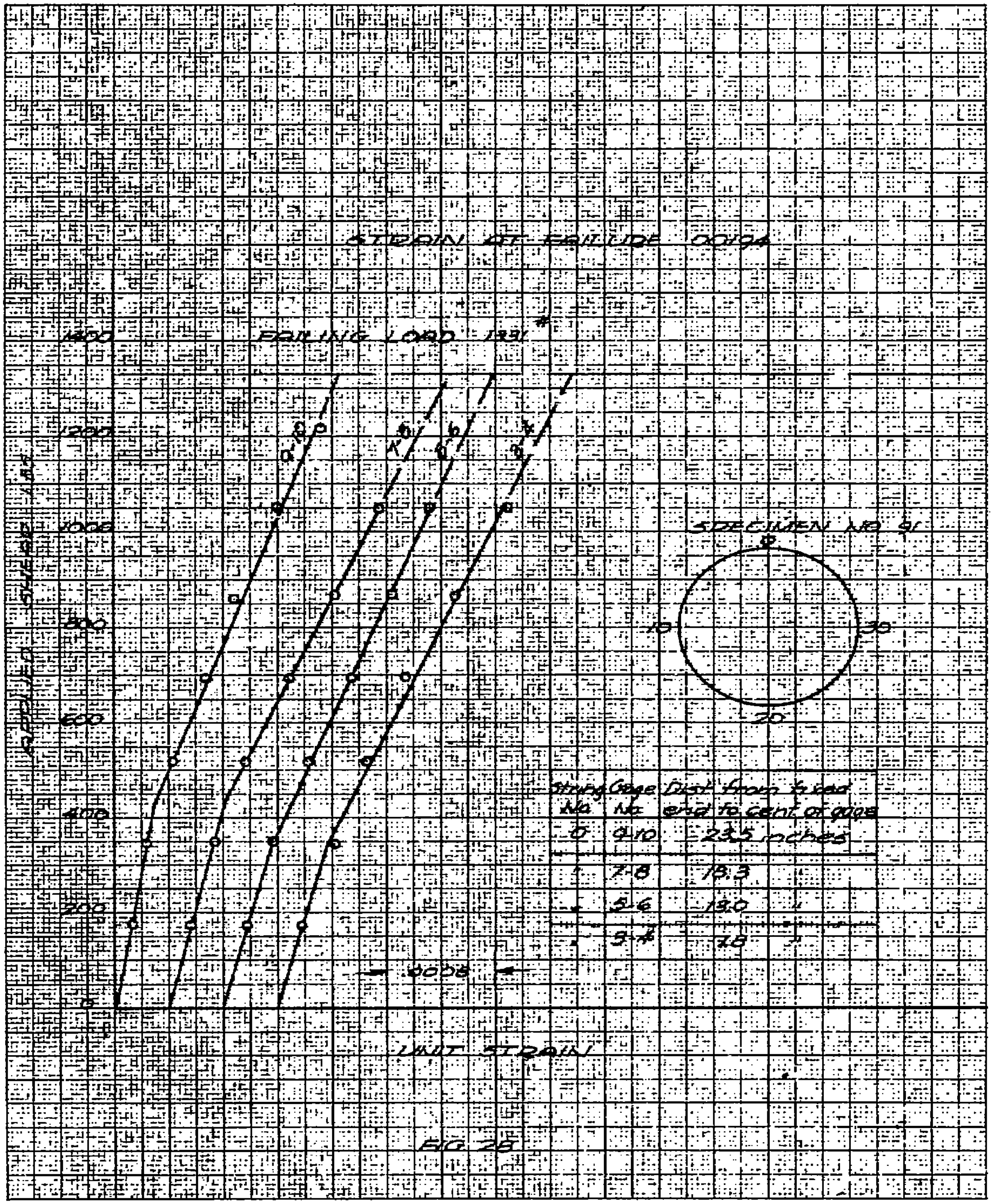


Fig. 27


STRAIN AT FAILURE .00194
FAILING LOAD 1331#
1400
1200
1000
800
600
400
200
0
APPLIED SHEAR LBS
SPECIMEN NO 91
10
20
30
String Gage Dist from fixed
No No end to cent of gage
0 9-10 23.5 inches
7-8 18.3
5-6 13.0
3-4 7.8
.0008
UNIT STRAIN
FIG 28

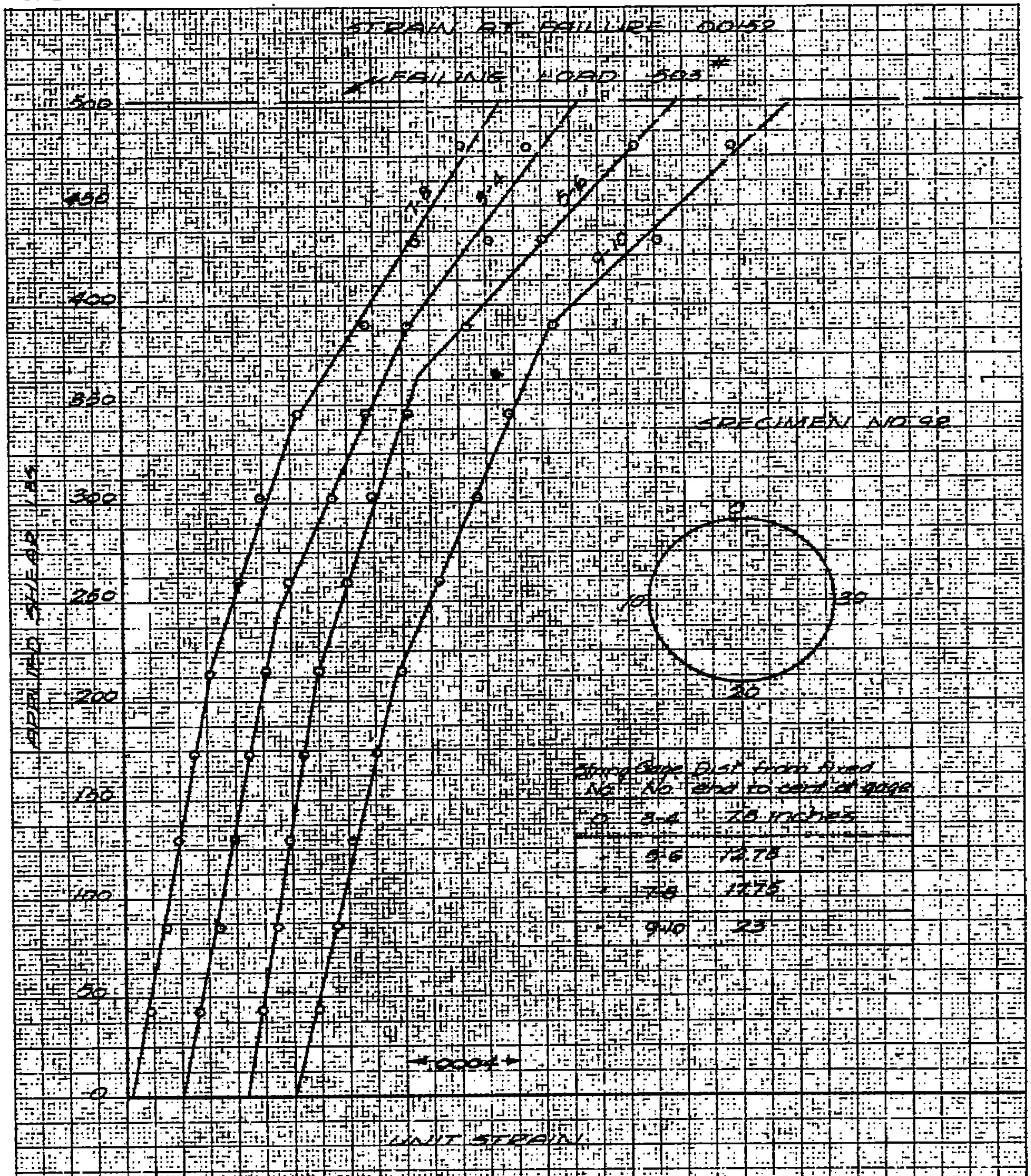

STRAIN AT FAILURE .00152
FAILING LOAD 503#
500
450
400
350
300
250
200
150
100
50
0
APPLIED SHEAR LBS.
SPECIMEN NO 92
10
20
30
.0004
Strain Gage No.
Dist. from fixed end to cent of gage
3-4 7.5 inches
5-6 12.75
7-8 17.75
9-10 23
UNIT STRAIN

FIG. 29

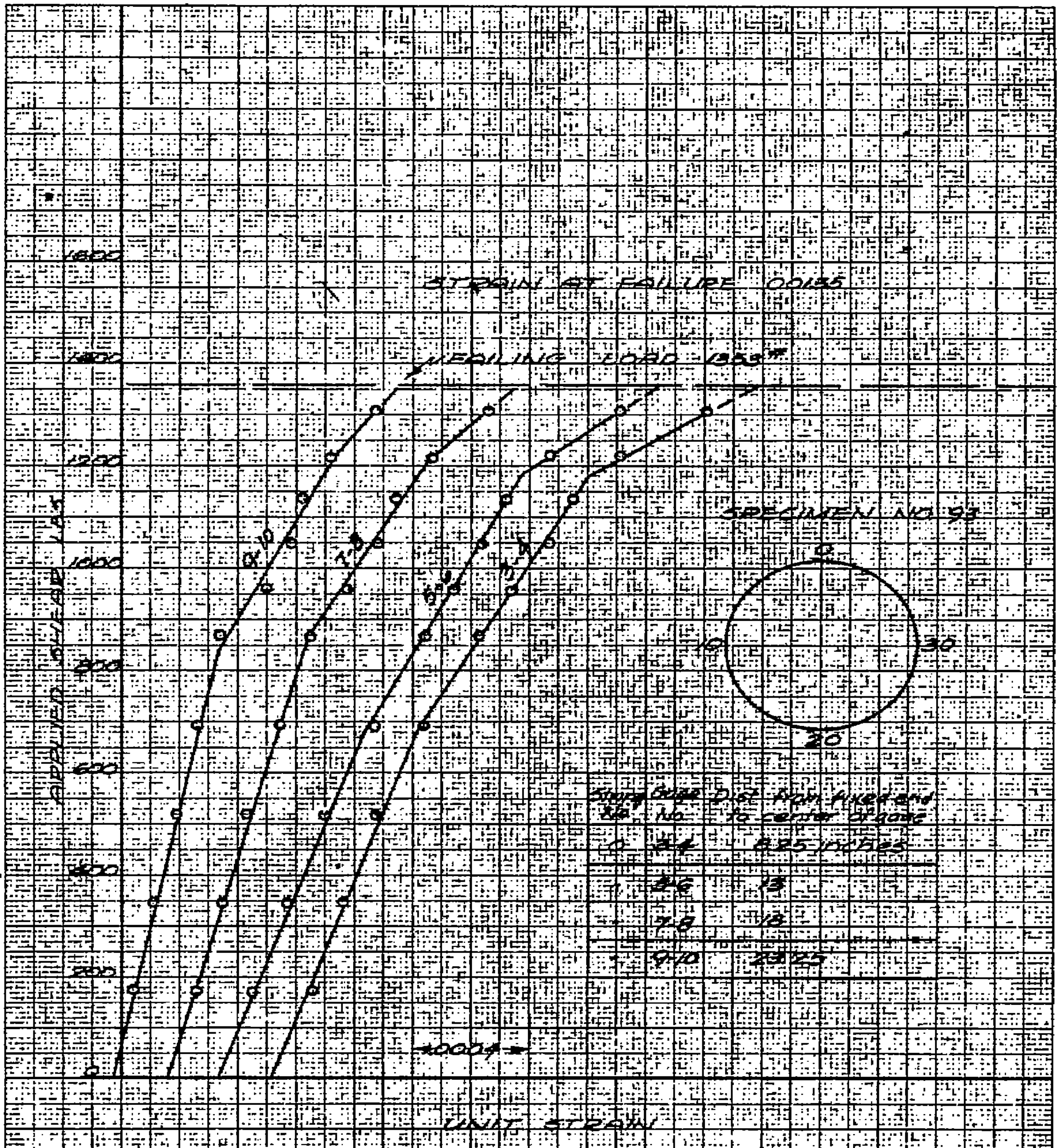
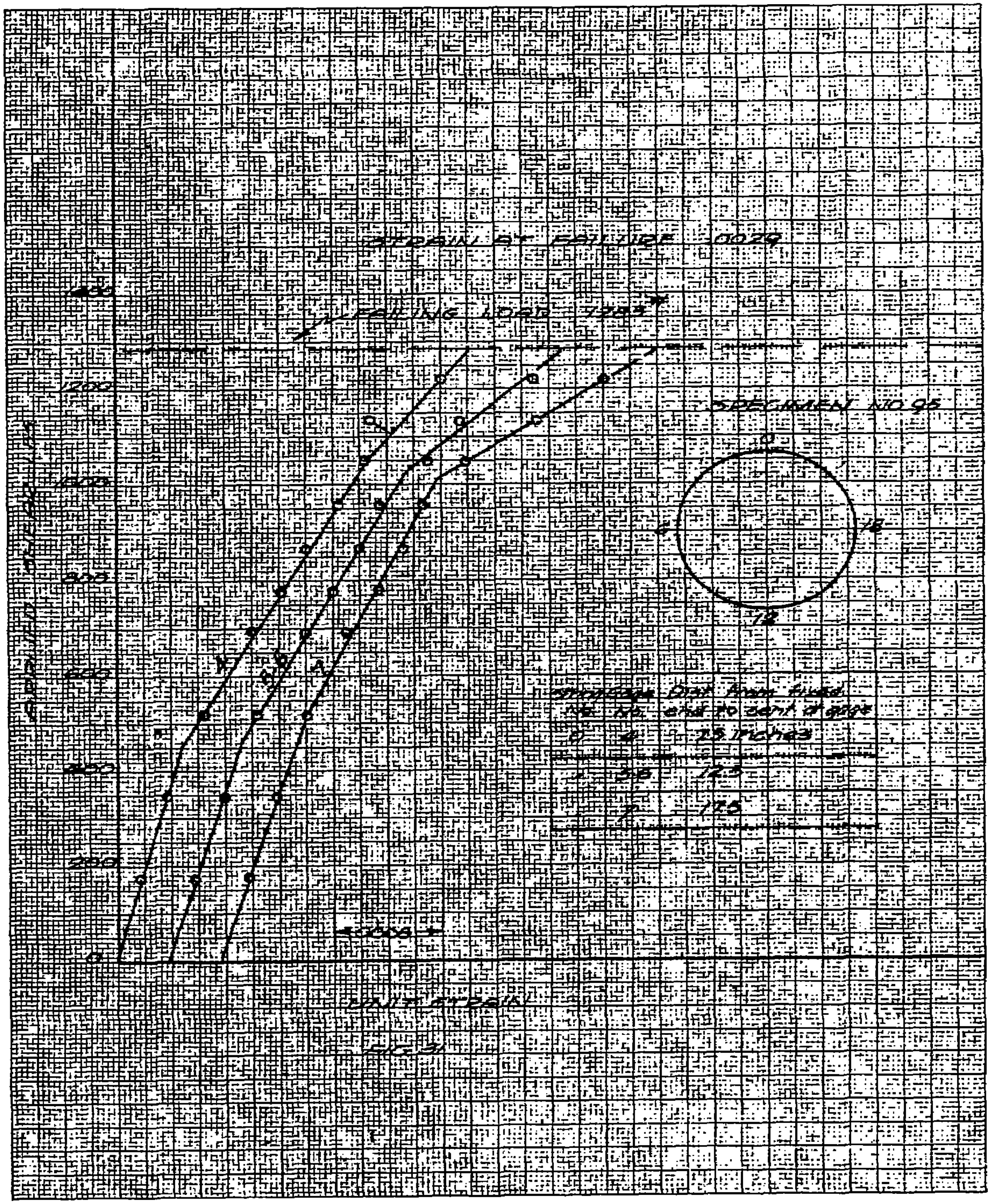

STRAIN AT FAILURE .00135
FAILING LOAD 1355#
SPECIMEN NO 93
APPLIED SHEAR LBS
1600
1400
1200
1000
800
600
400
200
0
10
20
30
.0004
UNIT STRAIN
Strain Gage No.
Dist. from fixed end to center of gage
3-4 8.25 inches
5-6 13
7-8 18
9-10 23.25

FIG. 30


STRAIN AT FAILURE .0029
FAILING LOAD 1285
SPECIMEN NO 95
1200
1000
800
600
400
200
0
25 inches
12.5
17.5
UNIT STRAIN

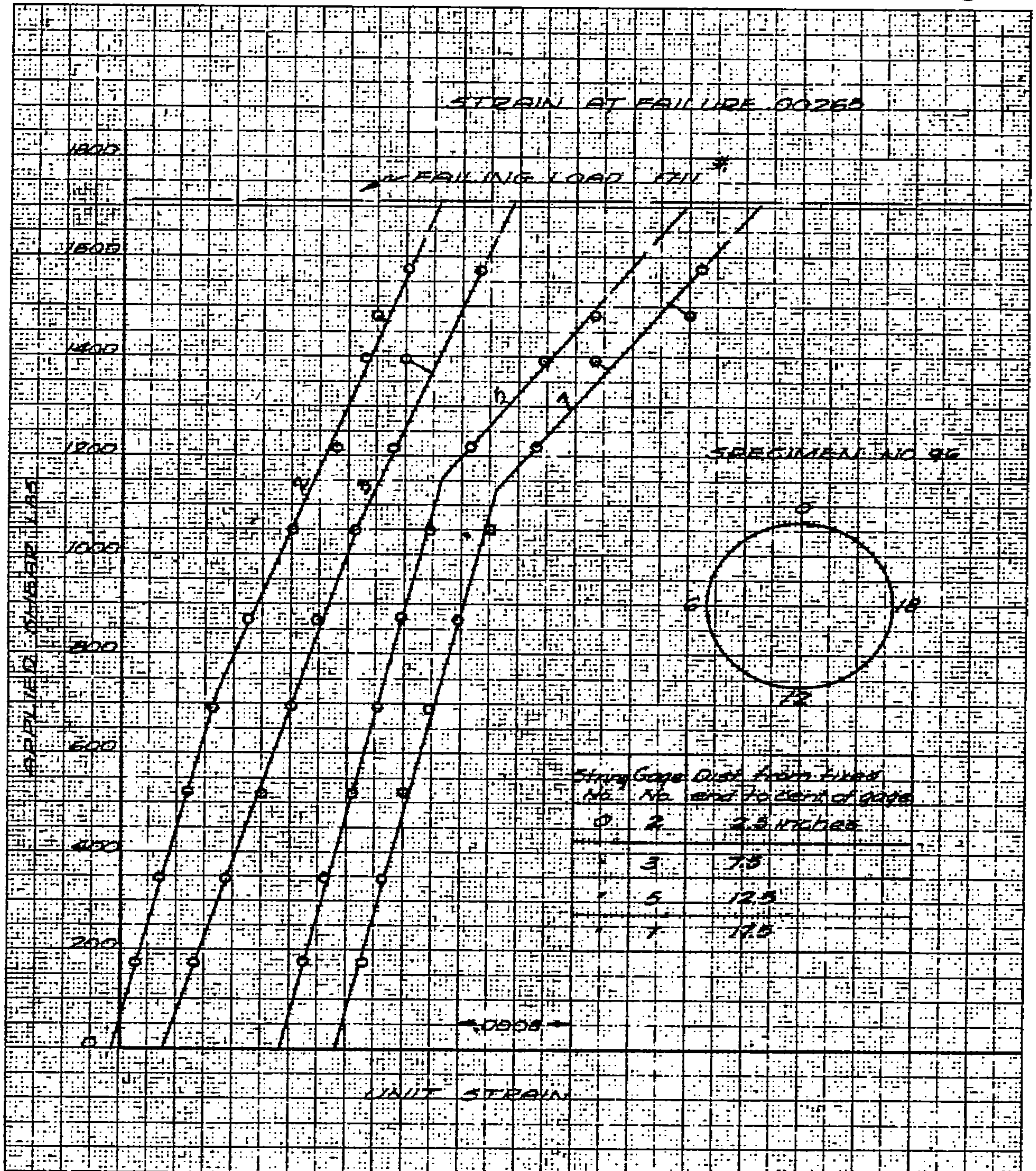

STRAIN AT FAILURE .00265
FAILING LOAD 1711
1800
1600
1400
1200
1000
800
600
400
200
0
APPLIED LOAD LBS
SPECIMEN NO 96
0
6
18
12
String No. | Gage No. | Dist. from fixed end and % cent of gage
0 2 2.5 inches
3 7.5
5 12.5
7 17.5
.0005
UNIT STRAIN

FIG. 32

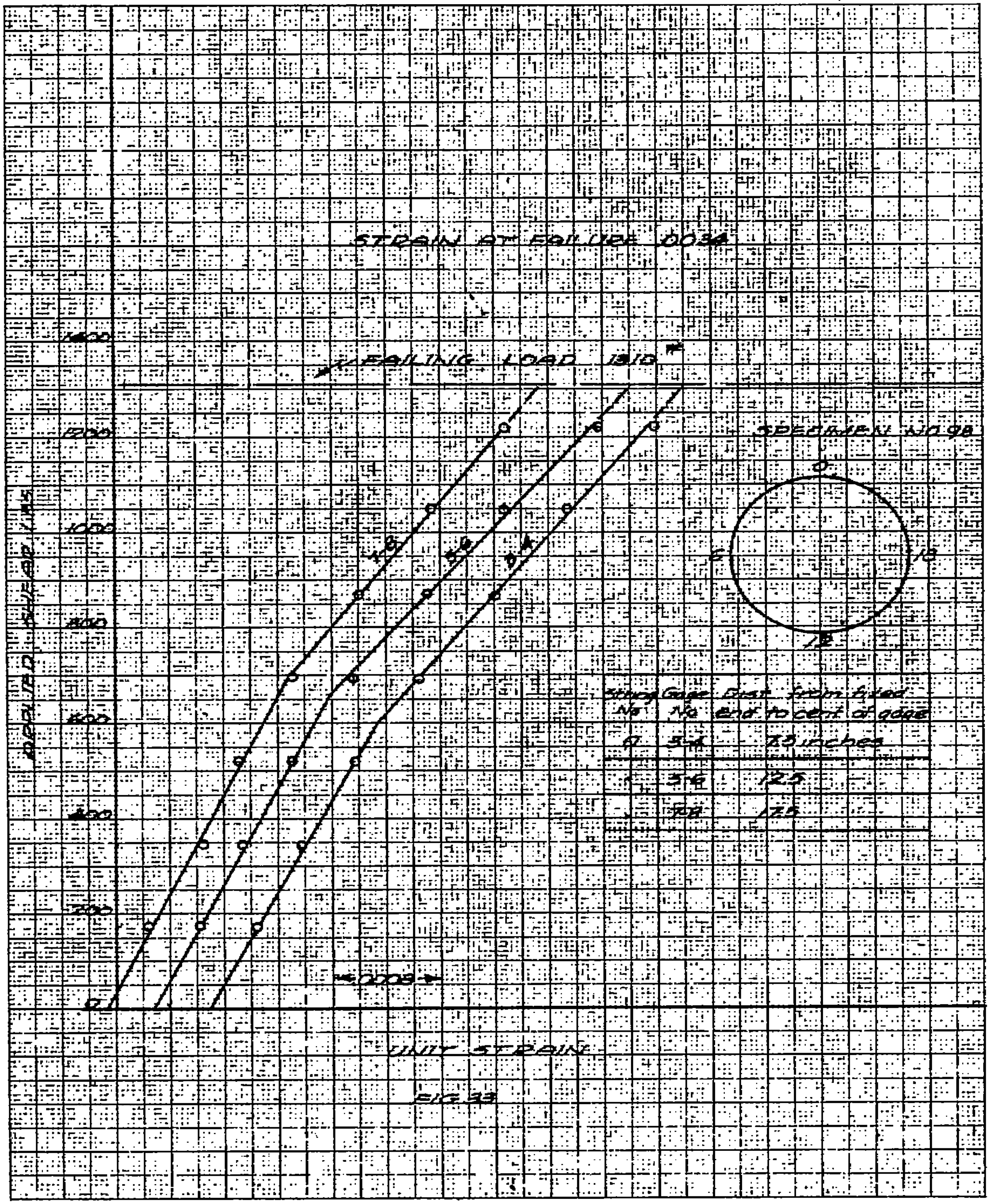
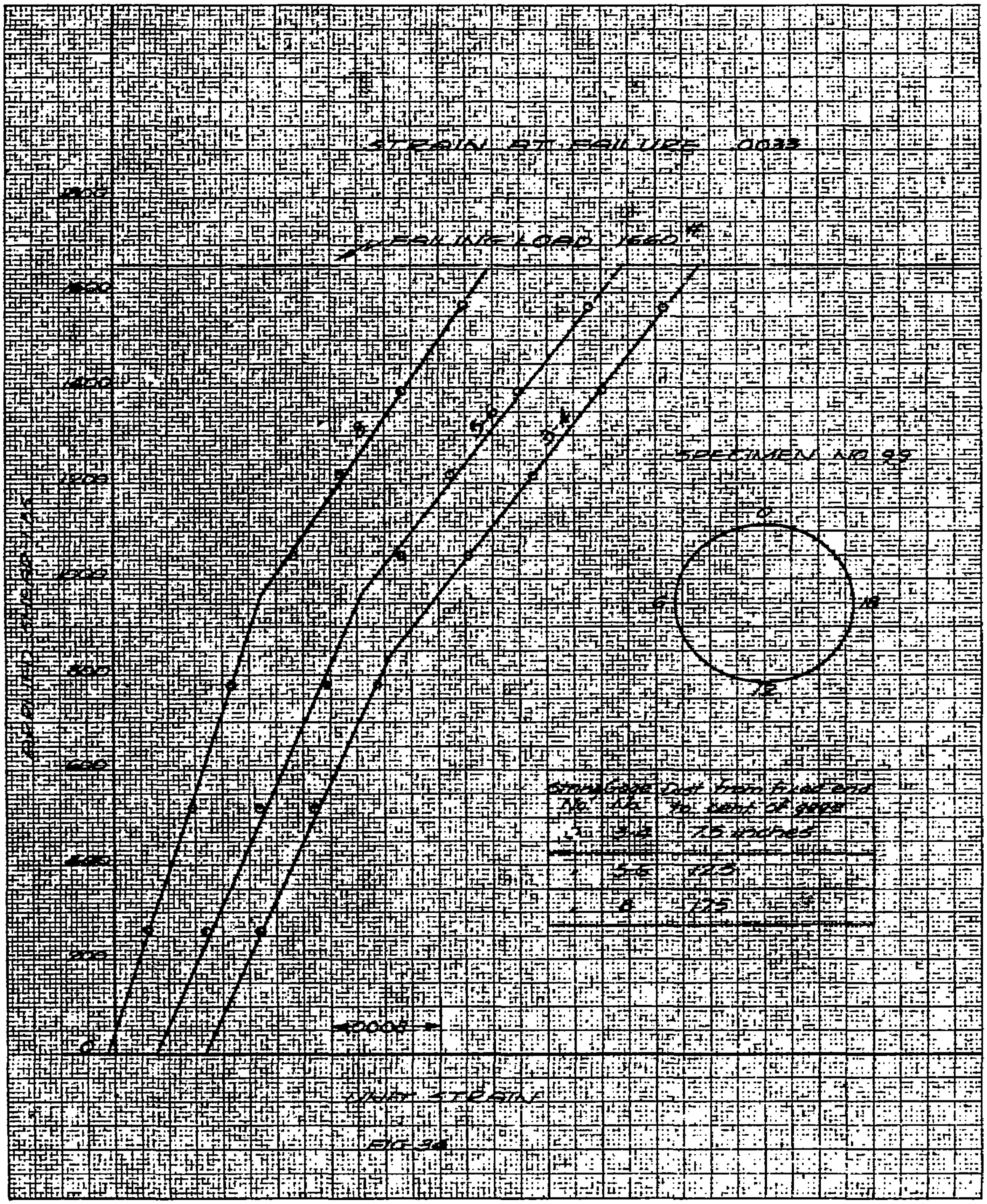
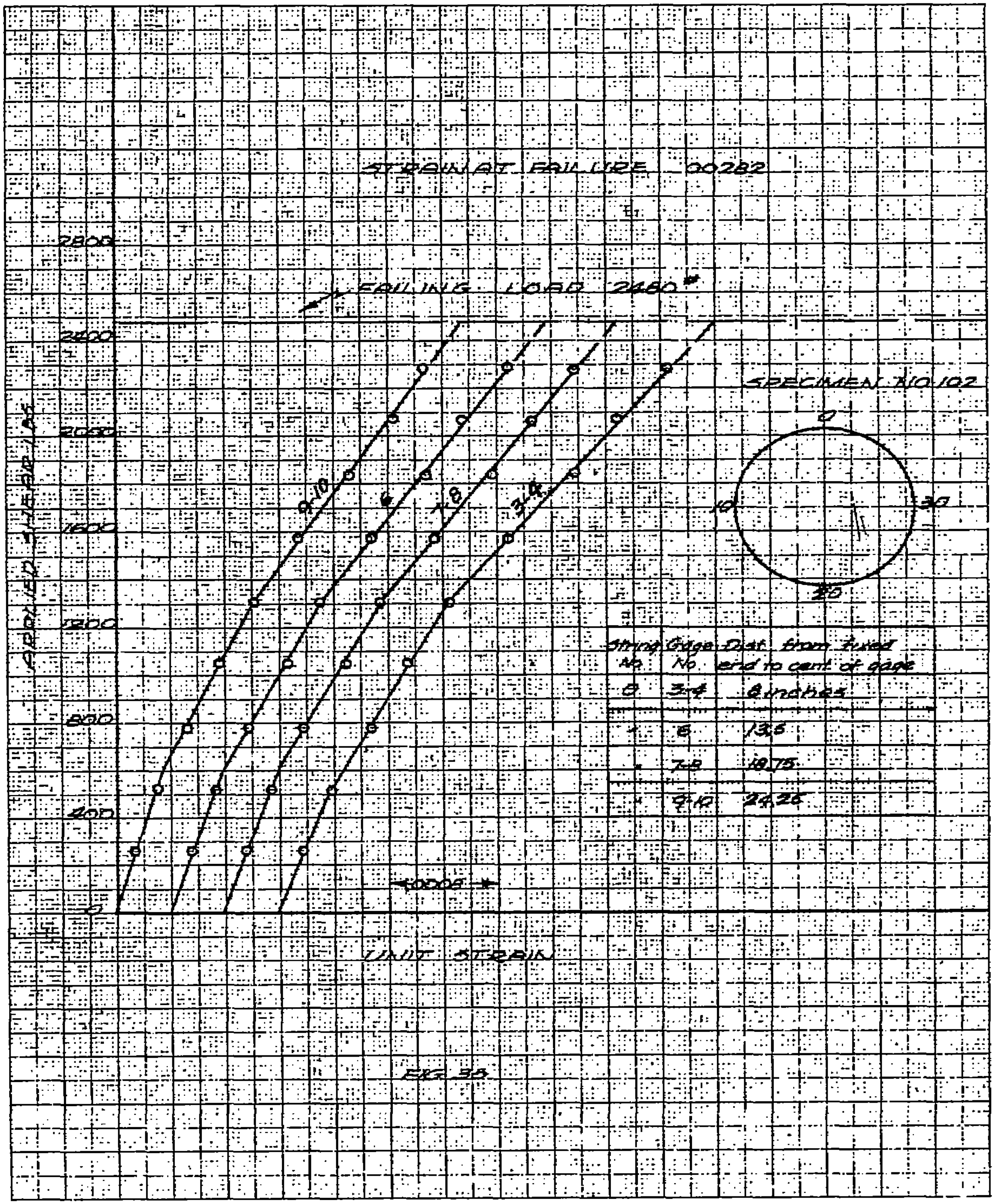
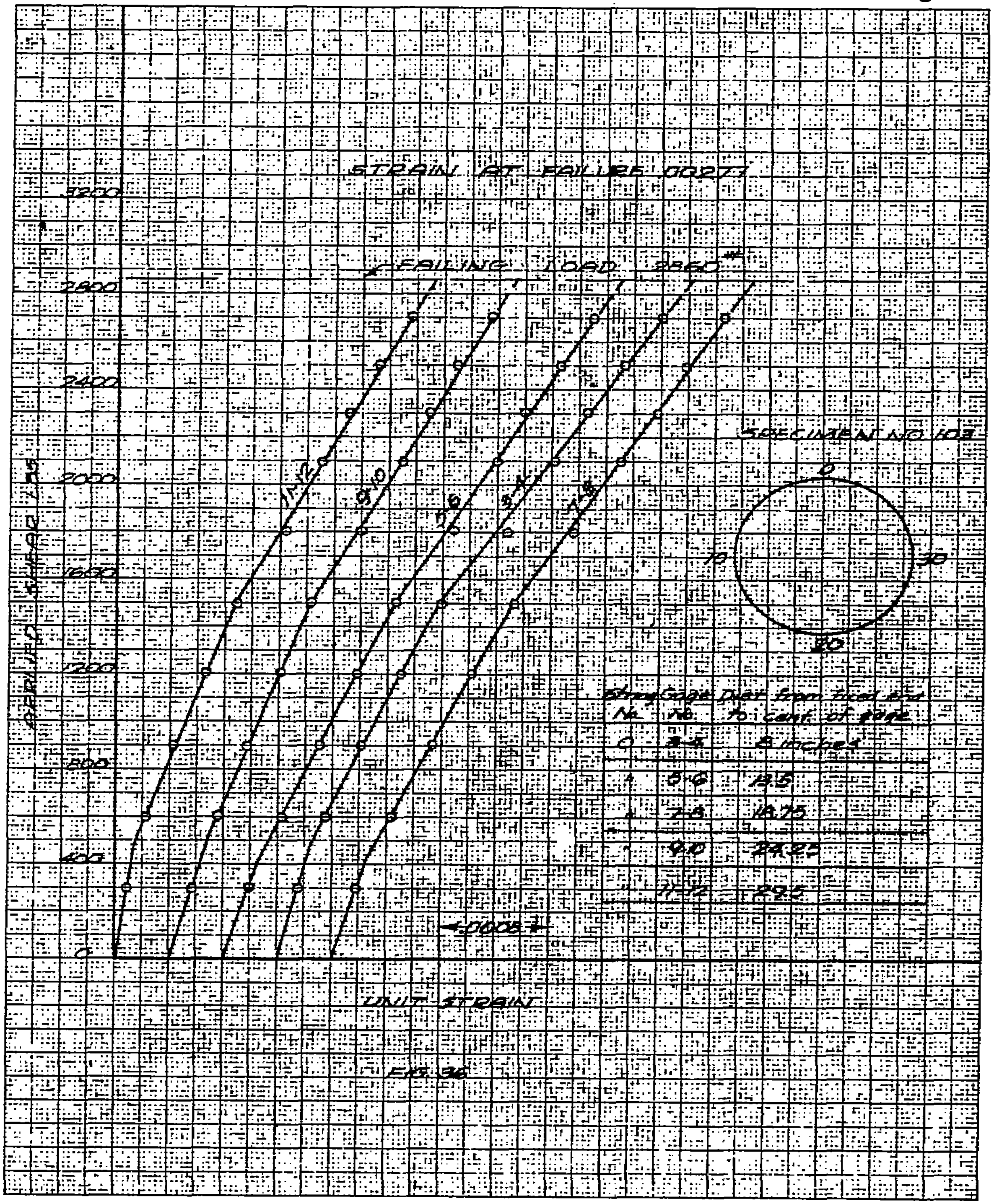
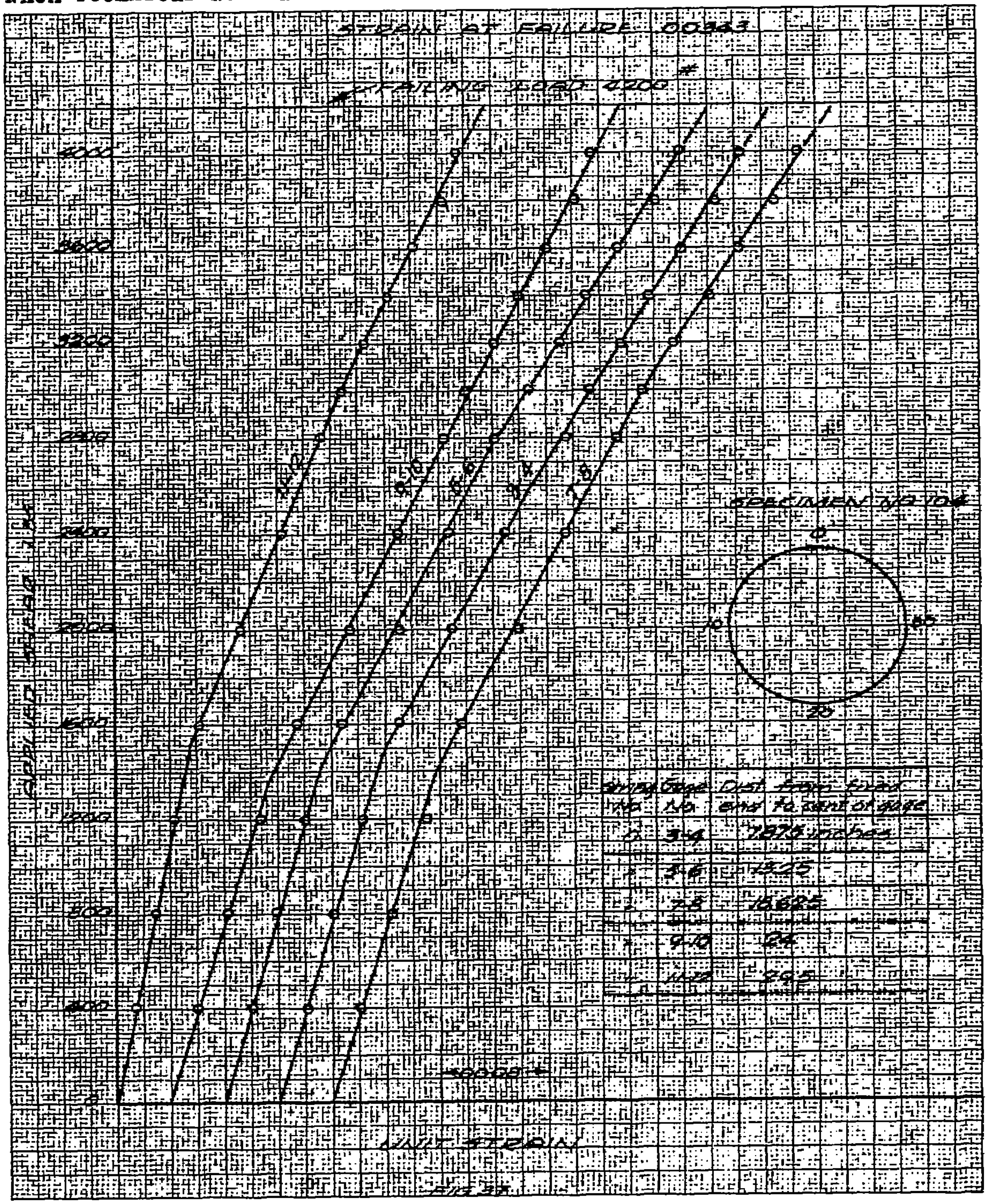

STRAIN AT FAILURE .0034
FAILING LOAD 1310#
SPECIMEN NO 9B
APPLIED SHEAR LBS
1400
1200
1000
800
600
400
200
0
.0003
UNIT STRAIN
String Gage Dist. from fixed
No. No. end to cent of gage
A 3-4 7.5 inches
5-6 12.5
7-8 17.5

FIG. 33


STRAIN AT FAILURE .0033
FAILING LOAD 1660 #
SPECIMEN NO 23
UNIT STRAIN
.0005
FIG 34


STRAIN AT FAILURE .00282
FAILING LOAD 2460#
2800
2400
2000
1600
1200
800
400
0
APPLIED LOAD-LBS
9-10
5-6
7-8
3-4
SPECIMEN NO 102
0
10
30
20
String Gage Dist. from fixed
No. No. end to cent. of gage
0 3-4 6 inches
5-6 13.5
7-8 18.75
9-10 24.25
.0005
UNIT STRAIN
FIG. 35


STRAIN AT FAILURE .00277
FAILING LOAD 2860#
3200
2800
2400
2000
1600
1200
800
400
0
APPLIED LOAD LBS
SPECIMEN NO 103
0
10
20
30
Strain Gage No. | Gage No. | Dist from fixed end to cent. of gage
0 | 3-4 | 8 inches
| 5-6 | 13.5
| 7-8 | 18.75
| 9-10 | 24.25
| 11-12 | 29.5
.0005
UNIT STRAIN
FIG. 36



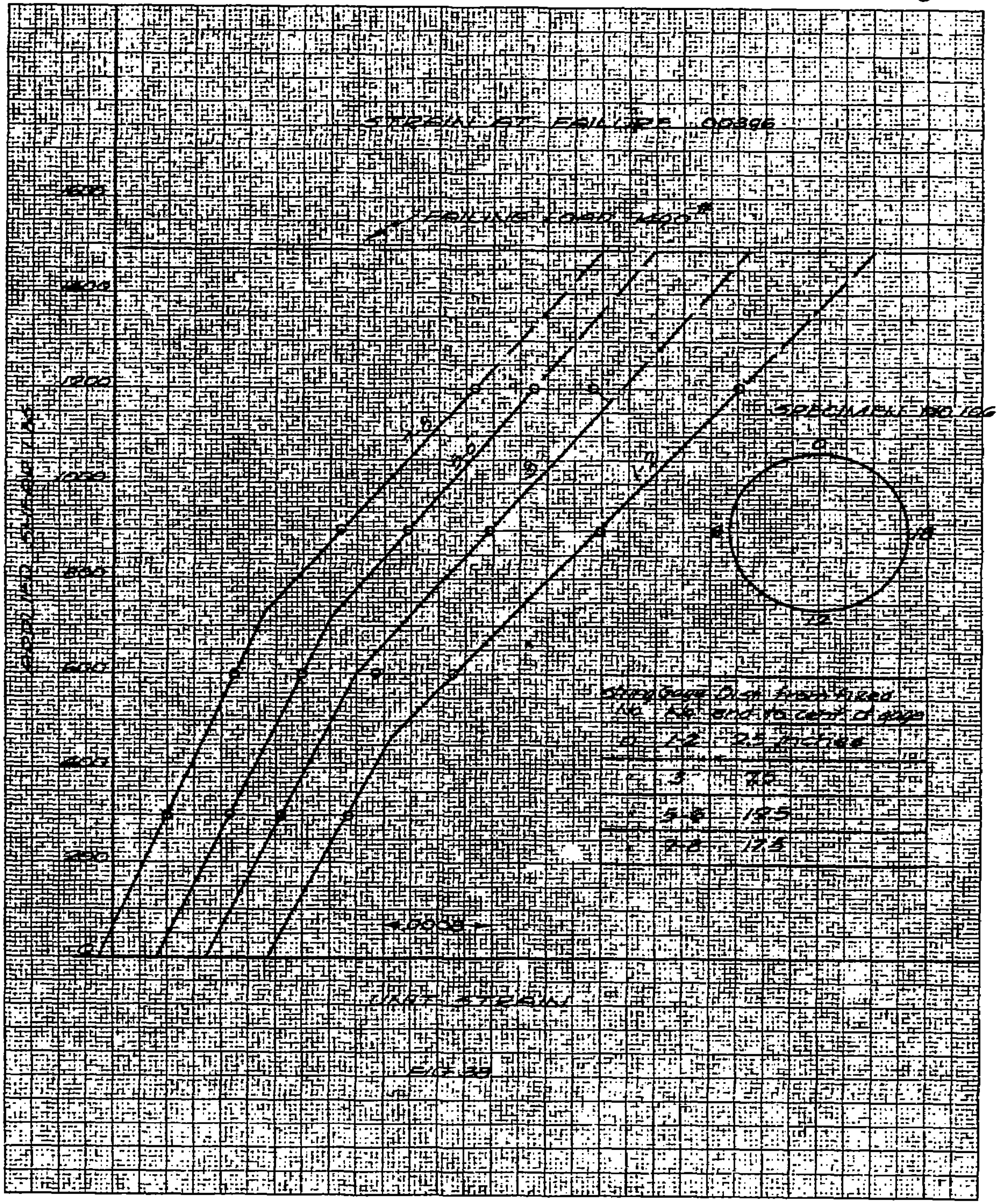
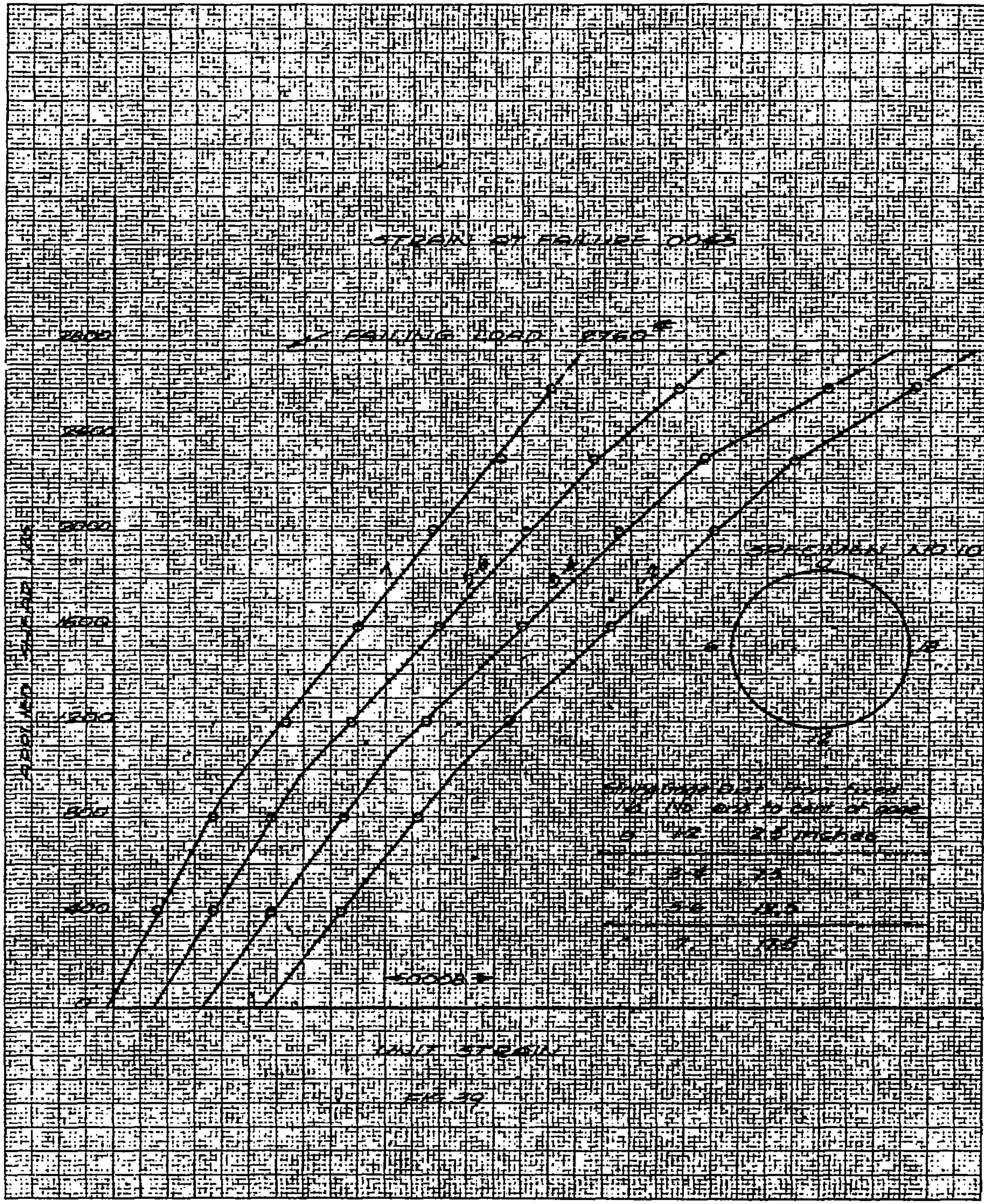

STRAIN AT FAILURE .00396
FAILING LOAD 1400#
SPECIMEN NO. 106
1600
1400
1200
1000
800
600
400
200
0
.0005
UNIT STRAIN
Strain Gage No.
Dist. from fixed end to cent of gage
1-2 2.5 inches
3 7.5
5-6 12.5
7-8 17.5

FIG 38


STRAIN AT FAILURE .0043
FAILING LOAD 2760#
APPLIED SHEAR LBS
SPECIMEN NO 107
UNIT STRAIN
FIG 39

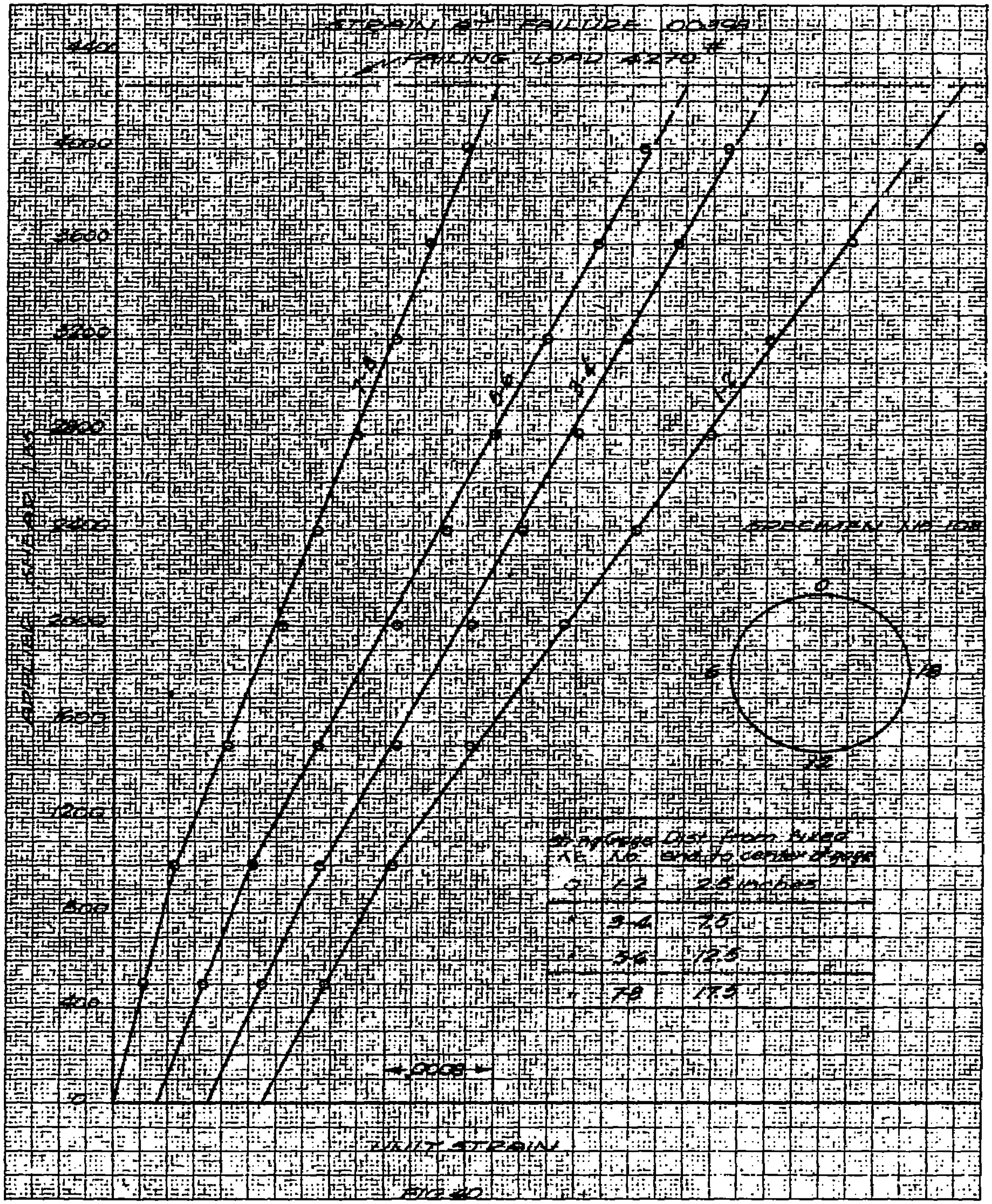
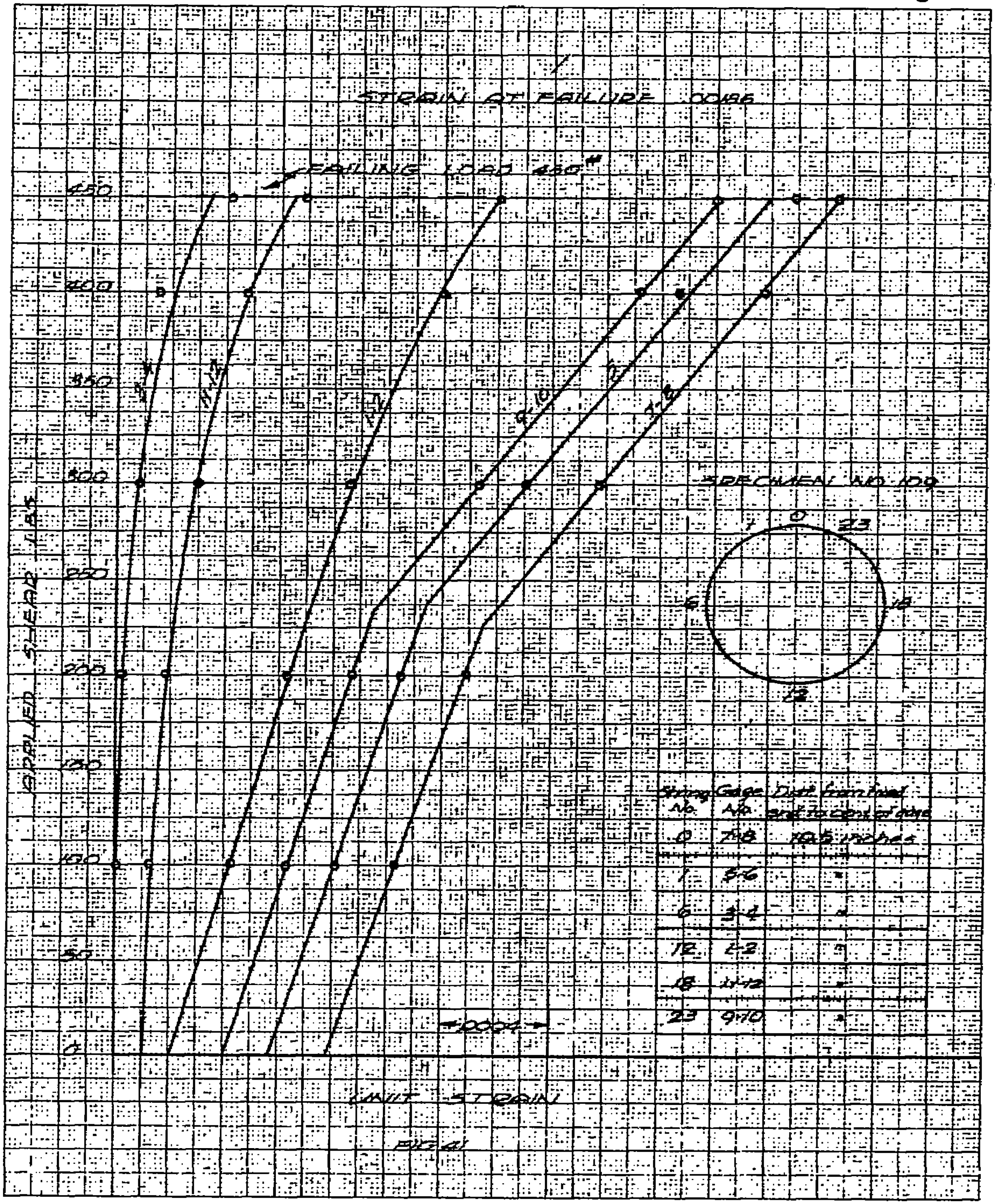
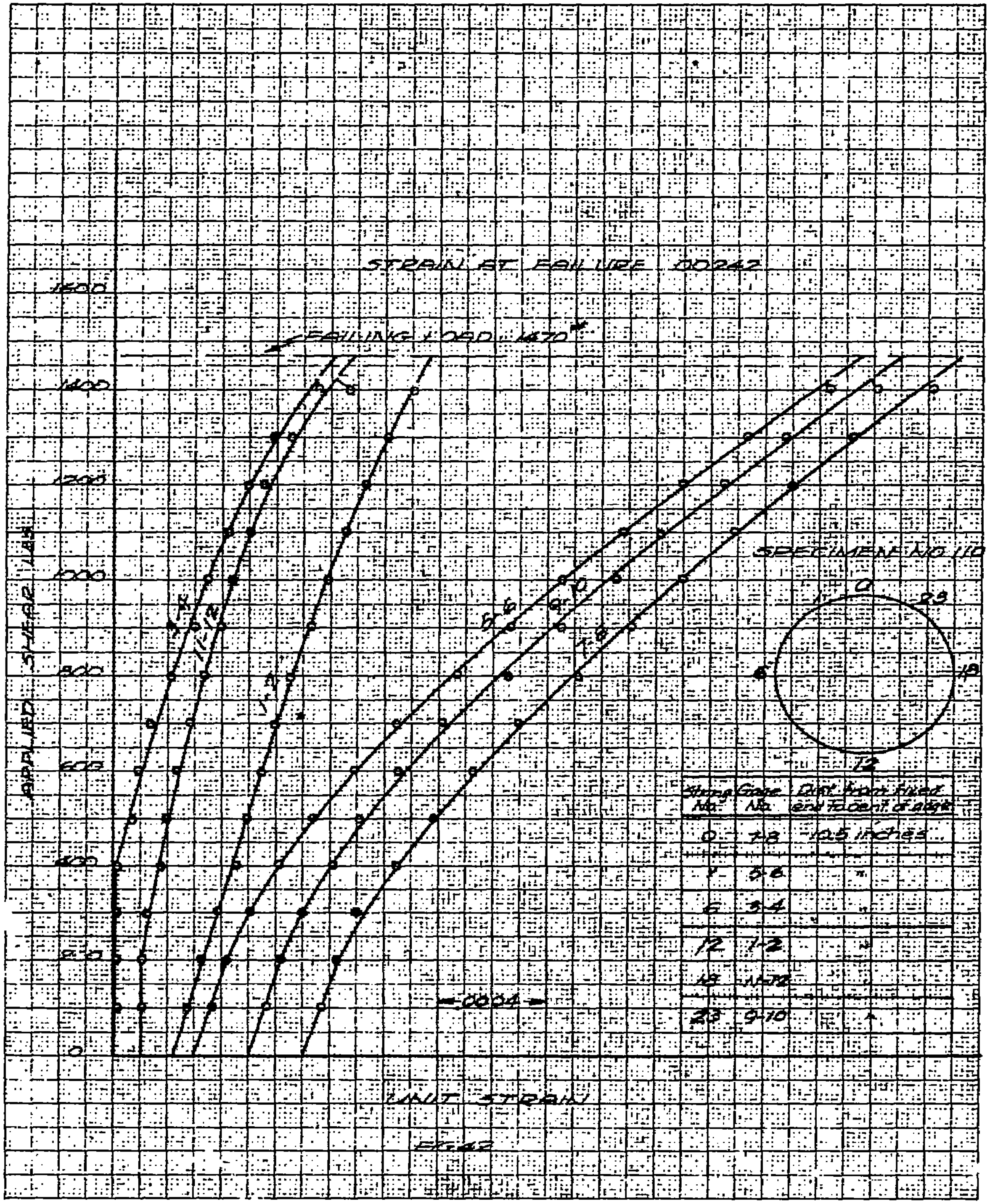
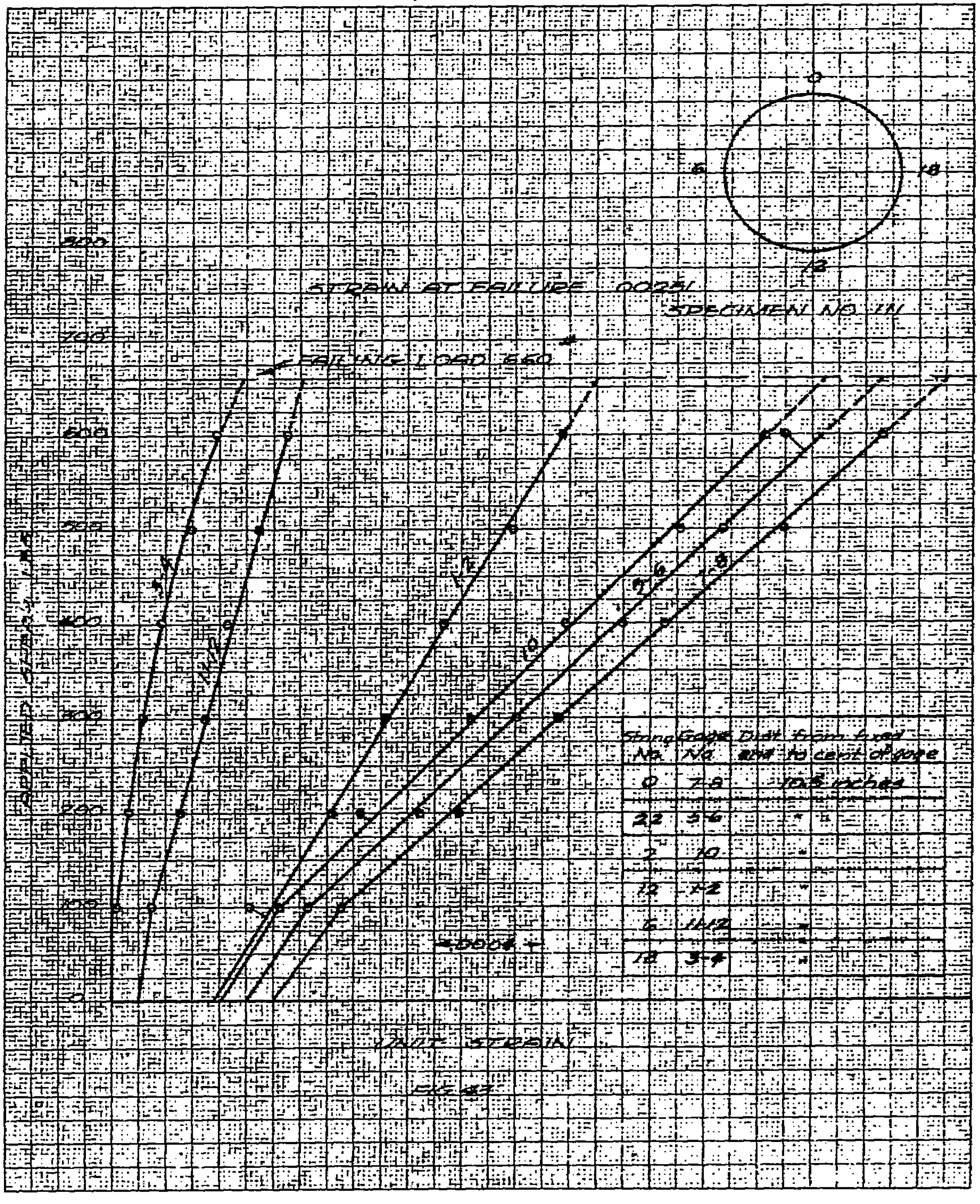
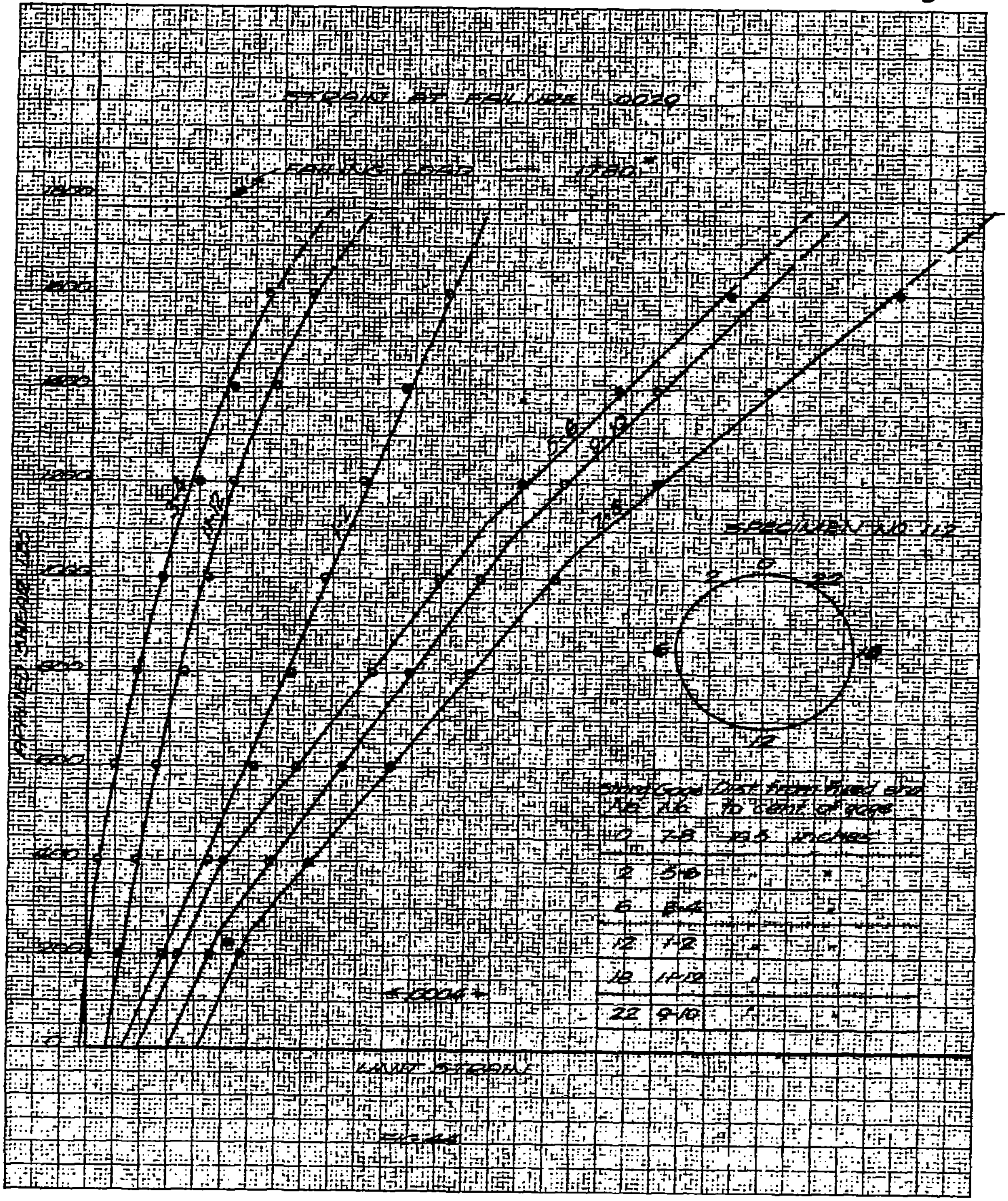

STRAIN AT FAILURE .00399
FAILING LOAD 4270 #
APPLIED LOAD LBS
UNIT STRAIN
.0008
SPECIMEN NO. 108
0
6
18
12
Strain gage No.
1-2
3-4
5-6
7-8
Dist. from fixed end to center of gage
2.5 inches
7.5
12.5
17.5

FIG. 40


STRAIN AT FAILURE .00186
FAILING LOAD 450#
450
400
350
300
250
200
150
100
50
0
APPLIED SHEAR LBS
SPECIMEN NO 109
0
1
23
6
18
12
String No.
Gage No.
Dist. from fixed end to cent. of gage
0 7-8 19.5 inches
1 5-6
6 3-4
12 1-2
18 11-12
23 9-10
.0004
UNIT STRAIN
FIG 41


STRAIN AT FAILURE .00242
FAILING LOAD 1470#
APPLIED SHEAR LBS
1600
1400
1200
1000
800
600
400
200
0
SPECIMEN NO 110
0
23
18
12
6
String Gage Dist from fixed
No. No. end to cent of gage
0 7-8 12.5 inches
5-6
6 3-4
12 1-2
9-10
.0004
UNIT STRAIN
FIG 42


STRAIN AT FAILURE .0025
SPECIMEN NO. 1N
FAILING LOAD 660#
APPLIED STRESS
UNIT STRAIN
.0004
Strng No. | Gage No. | Dist. from fixed end to cent. of gage
0 | 7-8 | 10.5 inches
22 | 5-6 | "
2 | 10 | "
12 | 1-2 | "
6 | 11-12 | "
18 | 3-4 | "
FIG 43



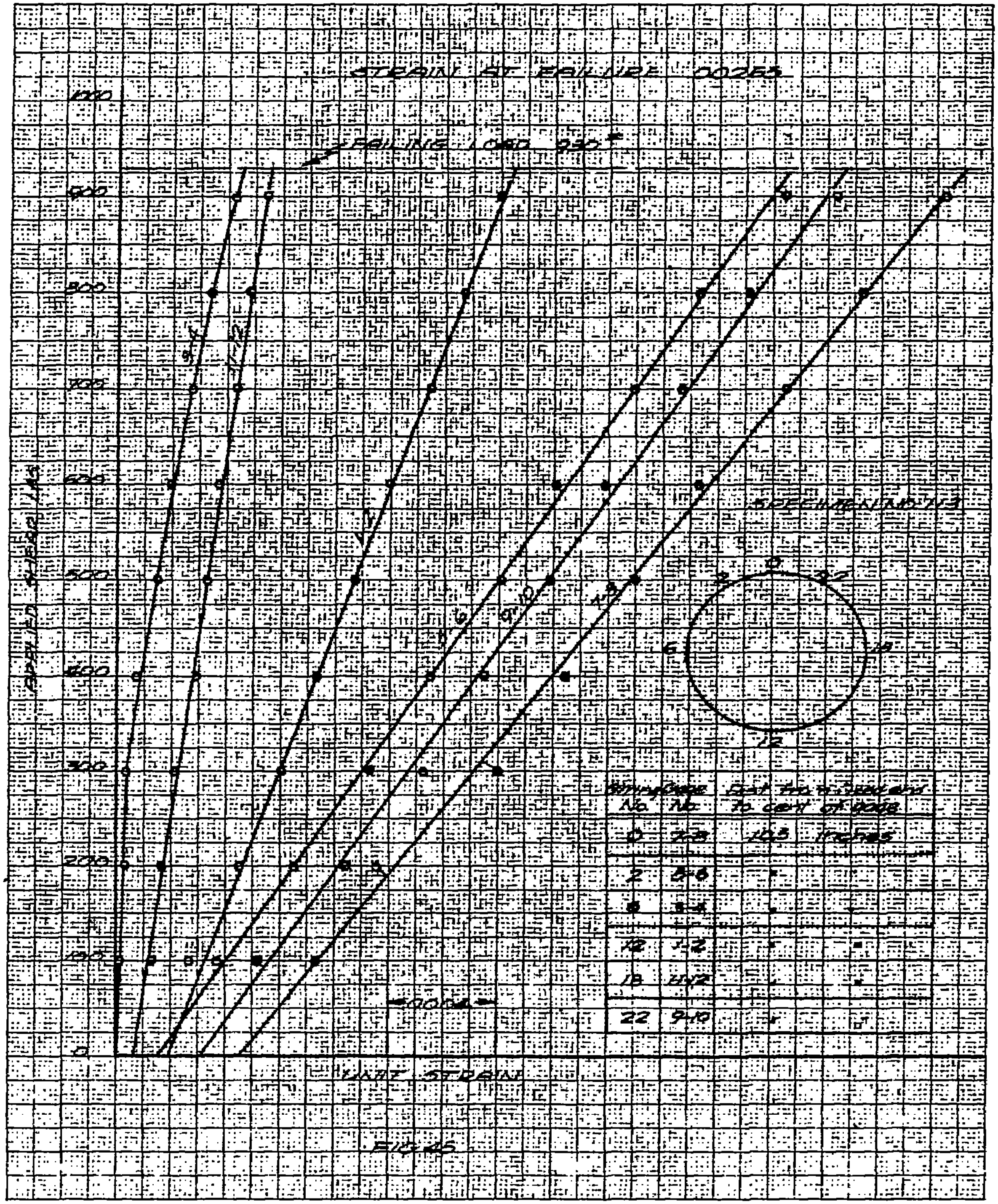
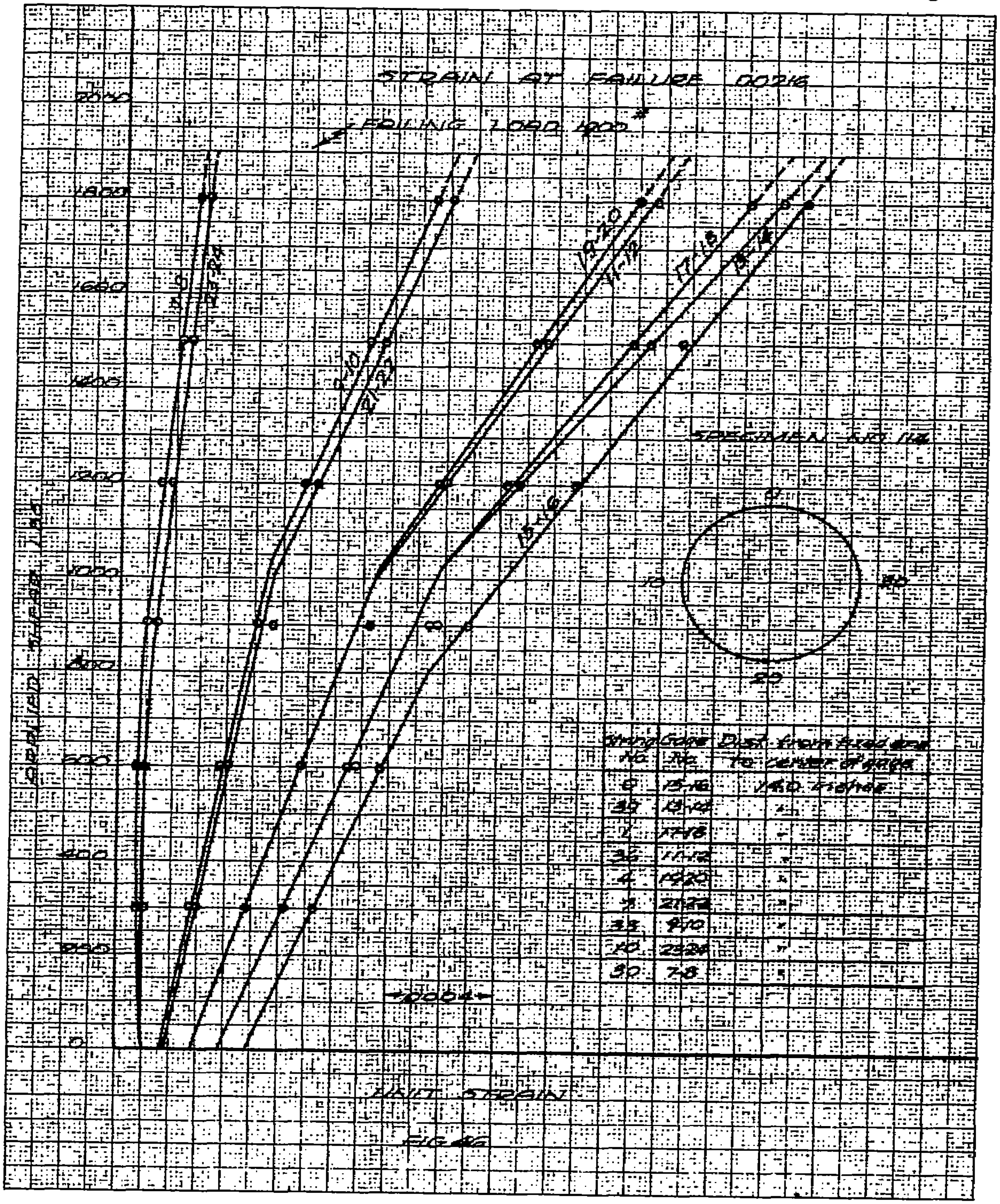

STRAIN AT FAILURE .00265
FAILING LOAD 930#
1000
900
800
700
600
500
400
300
200
100
0
APPLIED LOAD LBS
SPECIMEN NO 7-3
0
2
6
12
18
22
.0004
UNIT STRAIN
No.
No.
0
2-3
.103
inches
2
5-6
6
3-4
12
1-2
18
11-12
22
9-10

FIG 45


STRAIN AT FAILURE .00216
FAILING LOAD 1800#
SPECIMEN NO. 112
APPLIED STRESS LBS.
UNIT STRAIN
.0004
FIG. 46

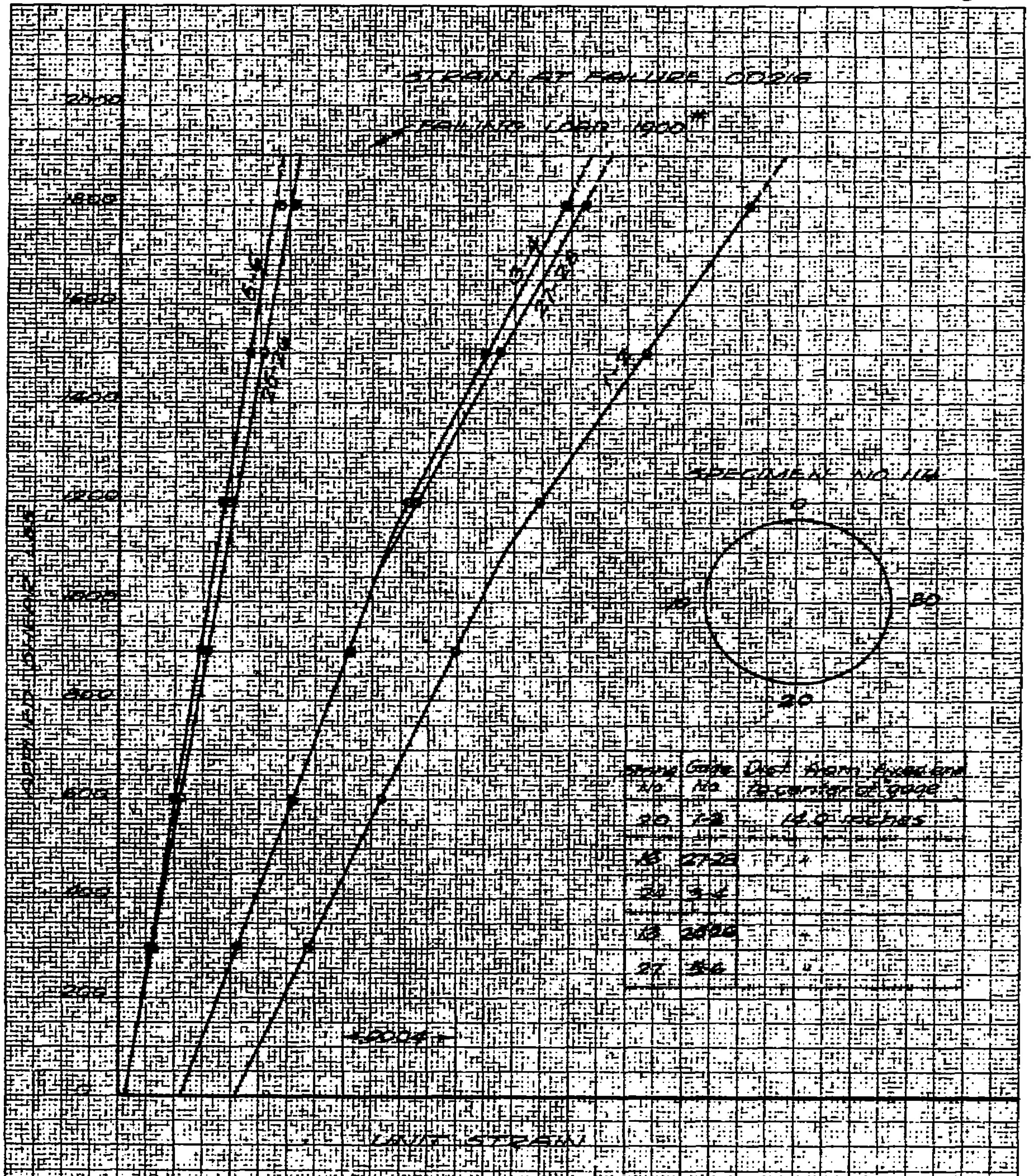
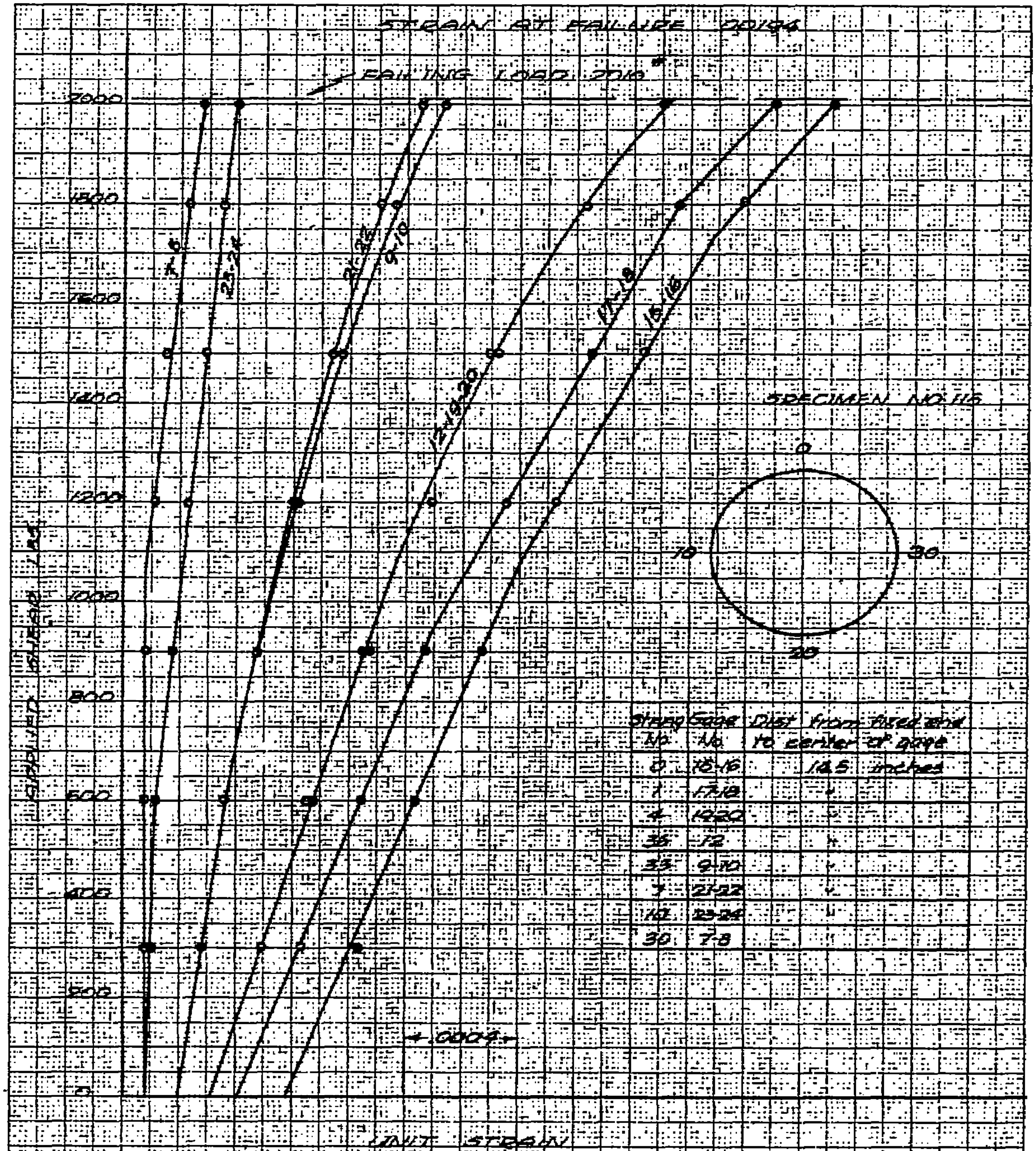
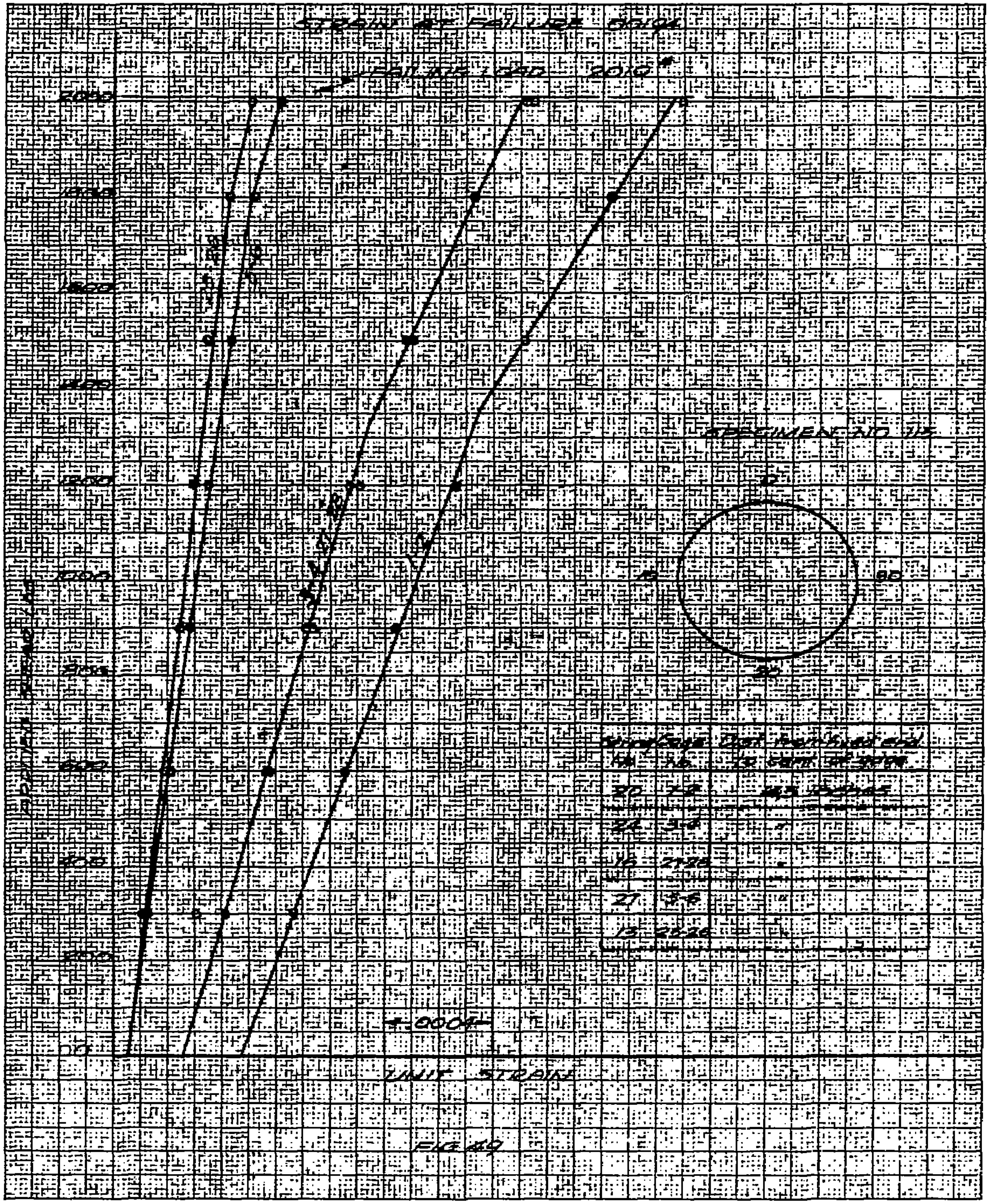

STRAIN AT FAILURE .00216
FAILURE LOAD 1900#
0
200
400
600
800
1000
1200
1400
1600
1800
2000
SPECIMEN NO. 114
0
80
20
.0004
UNIT STRAIN
APPLIED LOAD LBS

FIG. 47


STRAIN AT FAILURE .00194
FAILING LOAD 2010#
2000
1800
1600
1400
1200
1000
800
600
400
200
0
APPLIED AXIAL LOAD LBS
7-8
23-24
21-22
9-10
12-19-20
17-18
15-16
SPECIMEN NO. 115
0
30
20
70
Strap No. | Gage No. | Dist from fixed end to center of gage
0 | 15-16 | 14.5 inches
1 | 17-18
4 | 19-20
35 | 7-2
33 | 9-10
7 | 21-22
10 | 23-24
30 | 7-8
.0004
UNIT STRAIN
FIG. 48


FAILURE LOAD 2010#
2000
+.0004
UNIT STRAIN
FIG 49

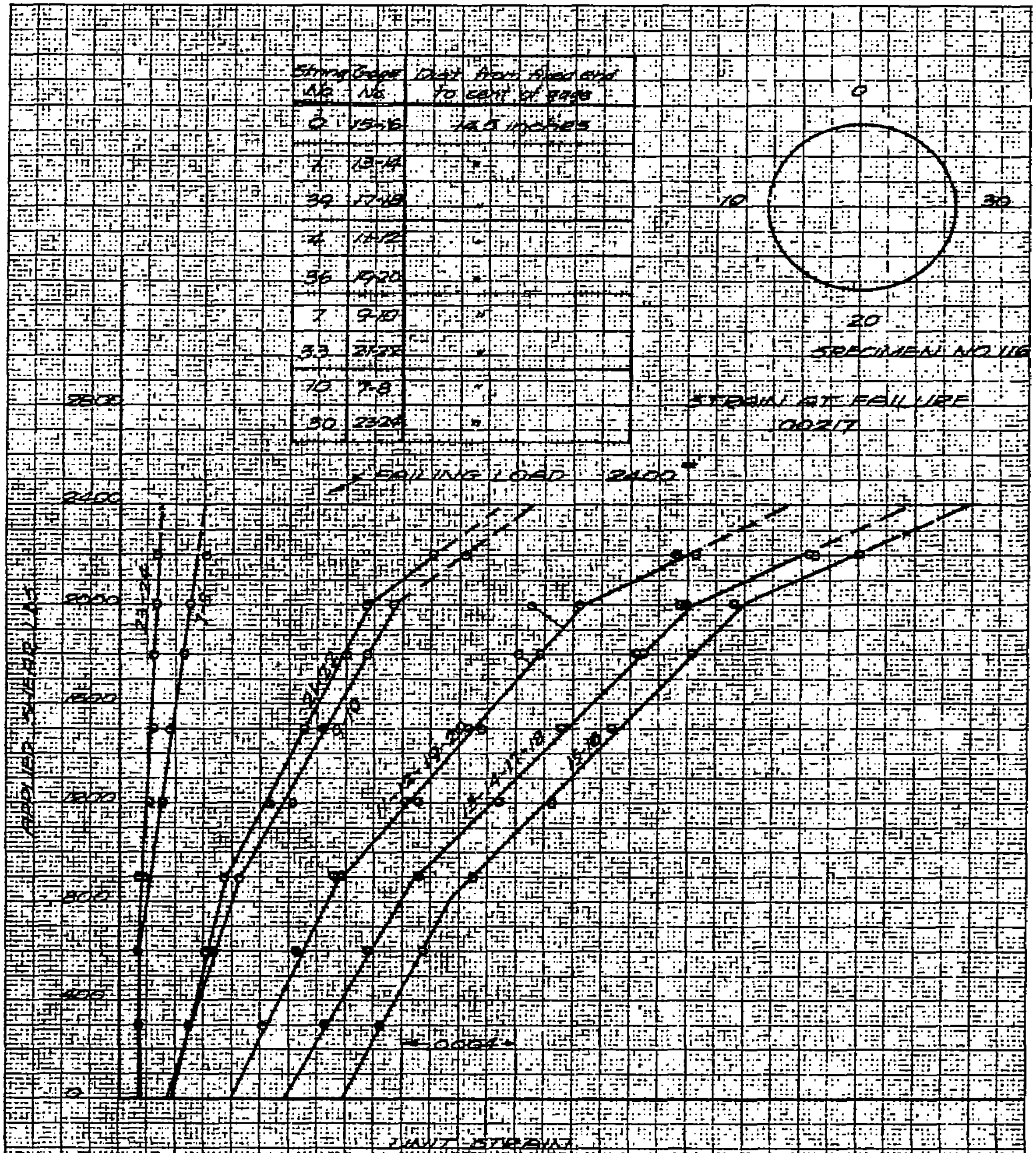

SPECIMEN NO. 11G
STRAIN AT FAILURE
.00217
FAILING LOAD 2400
APPLIED SHEAR (LB)
UNIT STRAIN
.0004
0
10
20
30
2800
2400
2000
1600
1200
800
400
0

FIG. 50

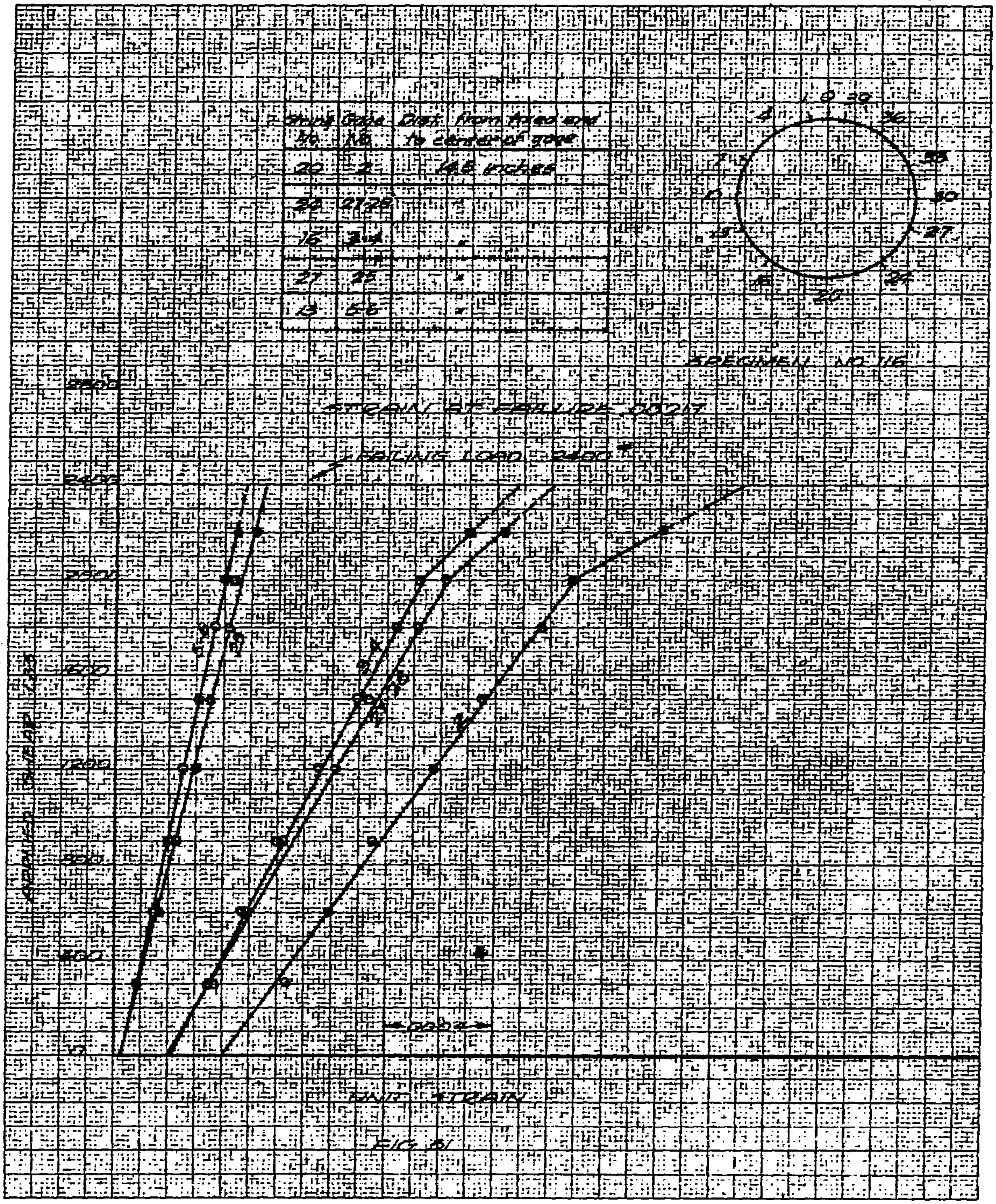
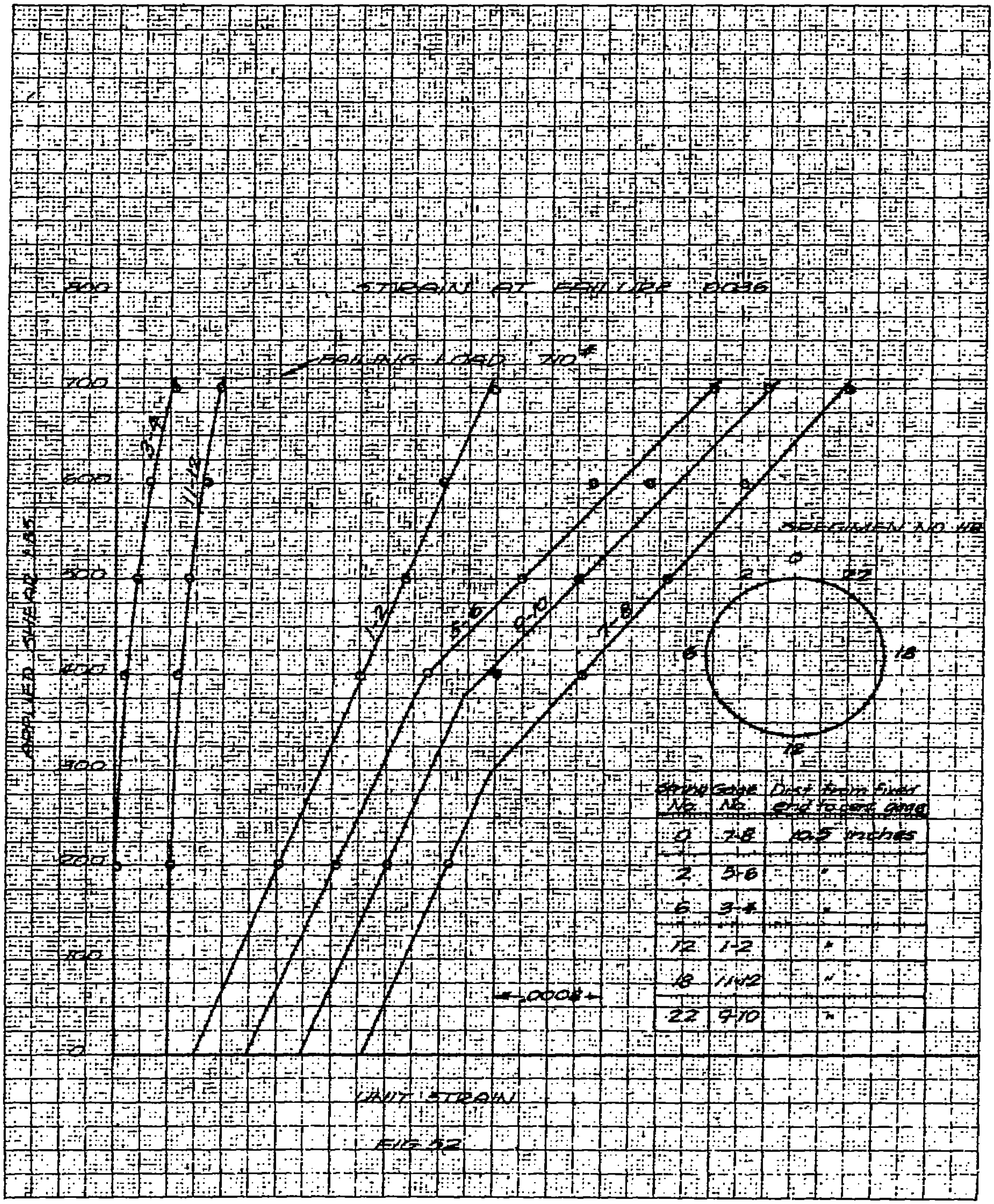
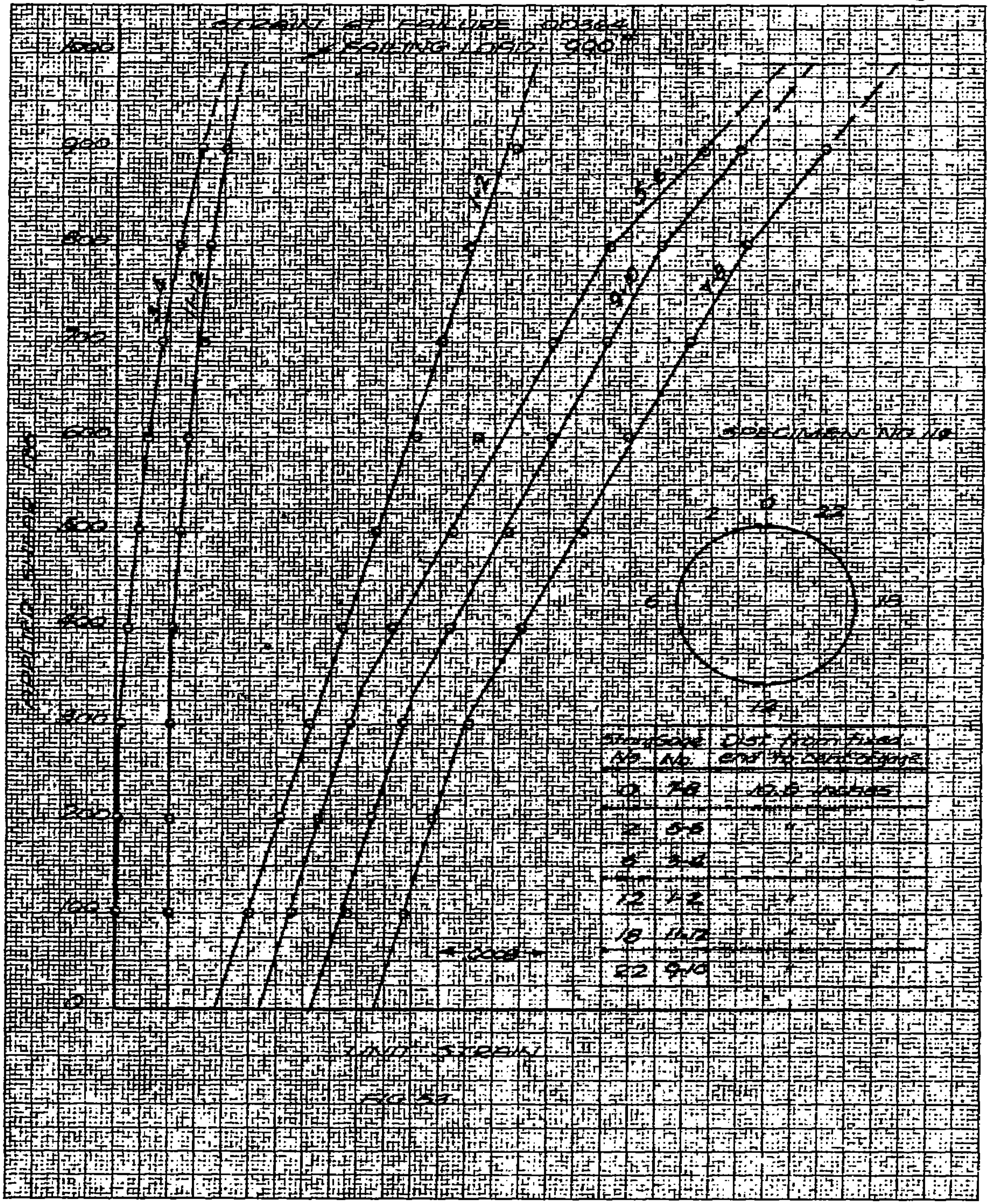


FIG. 51


STRAIN AT FAILURE .0036
FAILING LOAD 710#
800
700
600
500
400
300
200
100
0
APPLIED SHEAR LBS
3-4
11-12
1-2
5-6
9-10
7-8
0
2
6
12
18
22
Strain Gage No. | Gage No. | Dist from fixed end to cent gage
0 | 7-8 | 10.5 inches
2 | 5-6 | "
6 | 3-4 | "
12 | 1-2 | "
18 | 11-12 | "
22 | 9-10 | "
.0008
UNIT STRAIN
FIG 52


900
800
700
600
500
400
300
200
100
0
0 7-8 12.5 inches
2 5-6
6 3-4
12 1-2
18 11-12
22 9-10
UNIT STRAIN

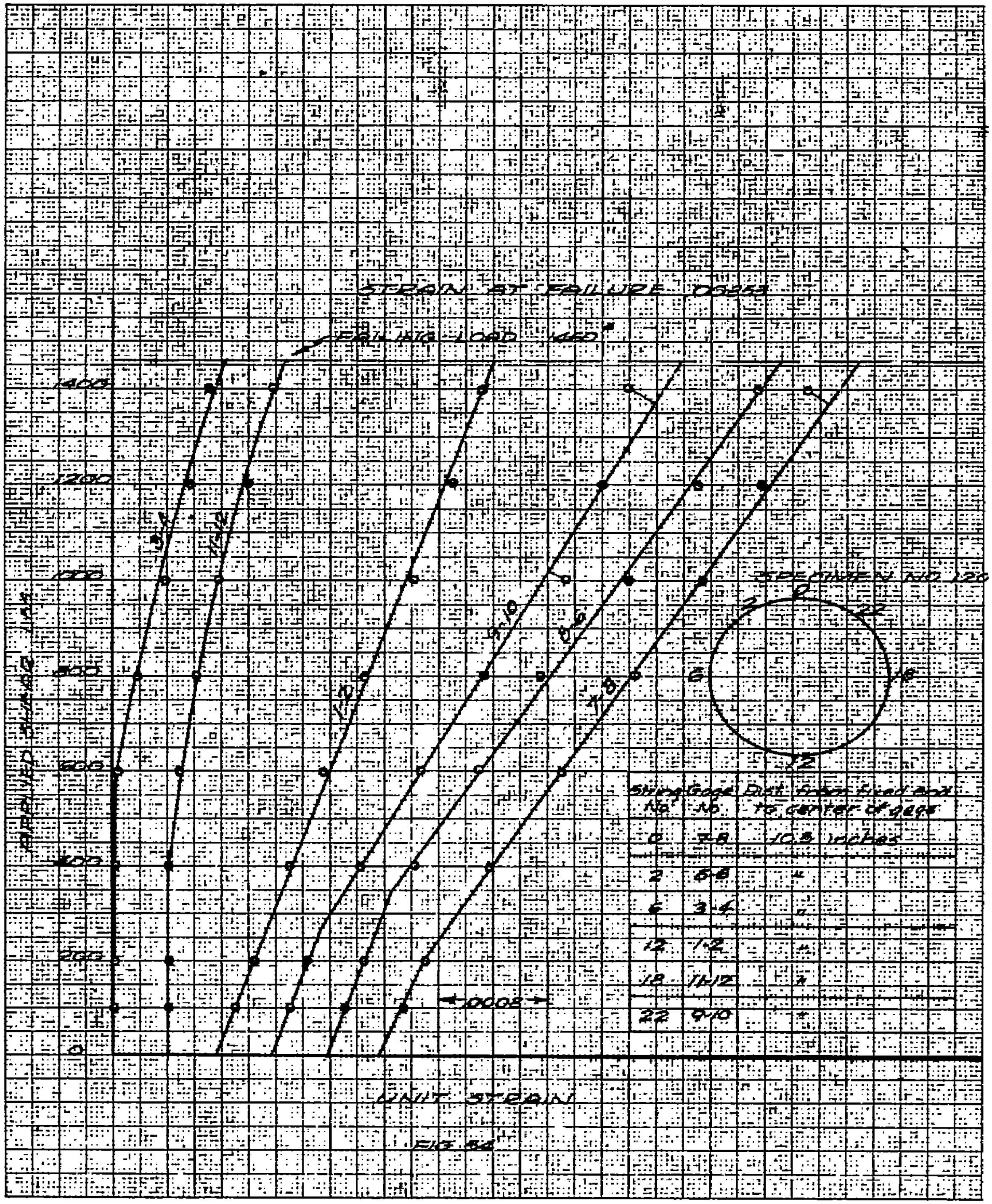
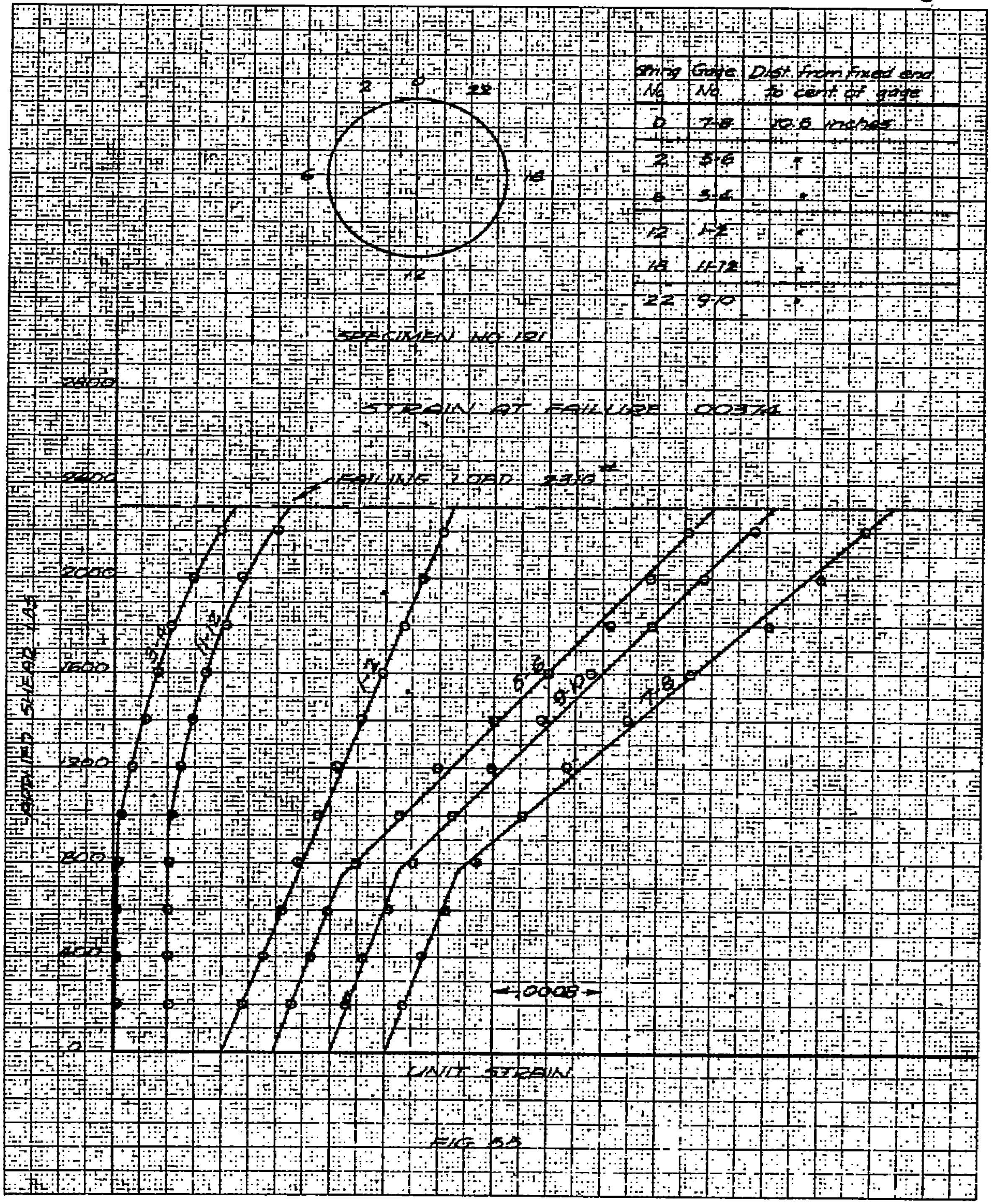

STRAIN AT FAILURE
FAILING LOAD 1460#
1400
1200
1000
800
600
400
200
0
.0002
UNIT STRAIN
SPECIMEN NO 120
0
2
22
6
18
12
Stringer No.
Gage No.
Dist from fixed end to center of gage
0 7-8 10.5 inches
2 5-6
6 3-4
12 1-2
18 11-12
22 9-10

FIG 54


String No.
Gage No.
Dist. from fixed end to cent of gage
0 7-8 10.6 inches
2 5-6
6 3-4
12 1-2
18 11-12
22 9-10
SPECIMEN NO. 121
STRAIN AT FAILURE .00374
FAILING LOAD 2310#
APPLIED SHEAR LBS
0
400
800
1200
1600
2000
2400
2800
3-4
11-12
1-2
5-6
9-10
7-8
.0008
UNIT STRAIN
FIG. 55

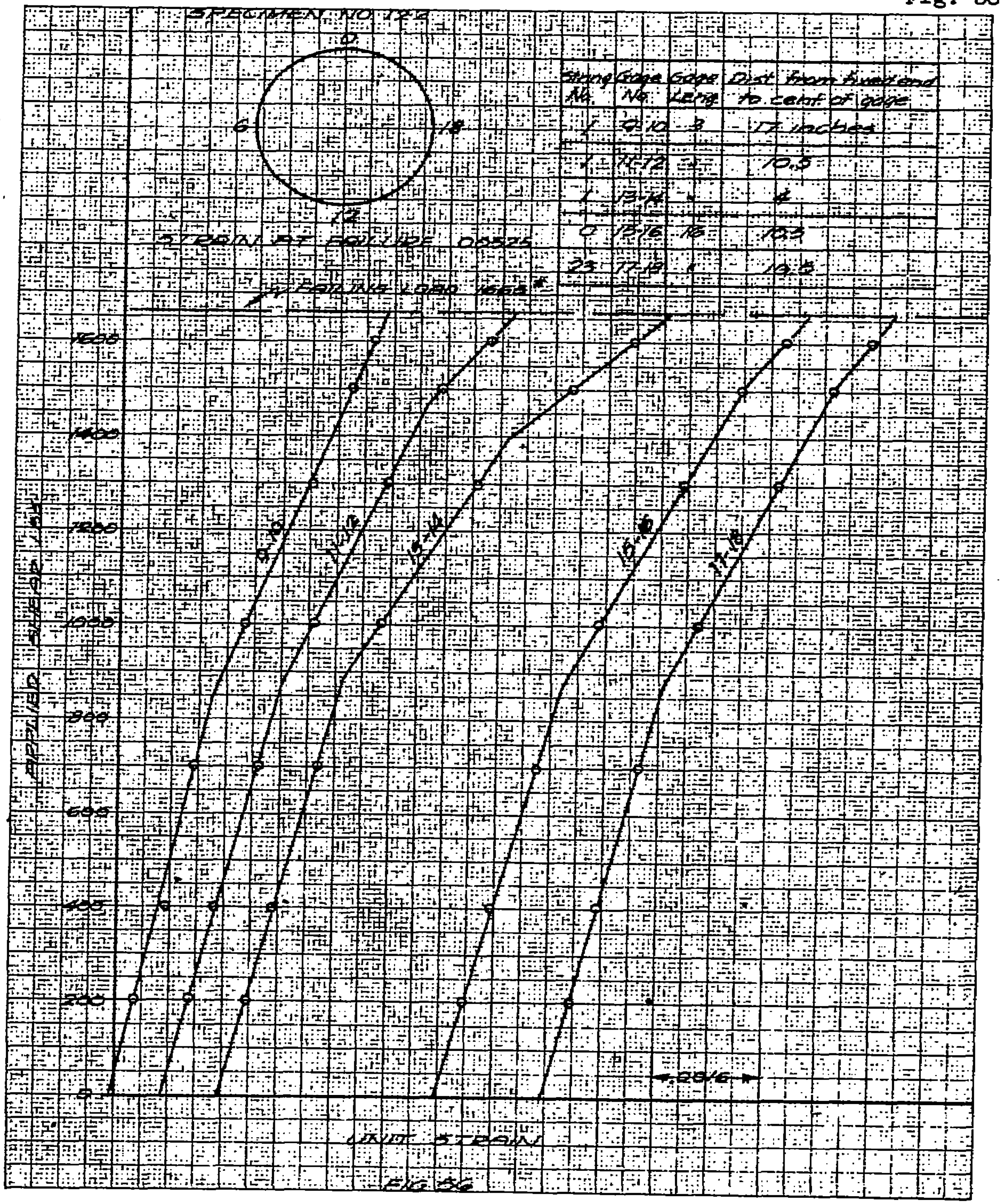

SPECIMEN NO 122
0
6
18
12
STRAIN AT FAILURE .00525
FAILING LOAD 1664 #
1600
1400
1200
1000
800
600
400
200
0
APPLIED LOAD LBS
9-10
11-12
13-14
15-16
17-18
UNIT STRAIN

FIG 56

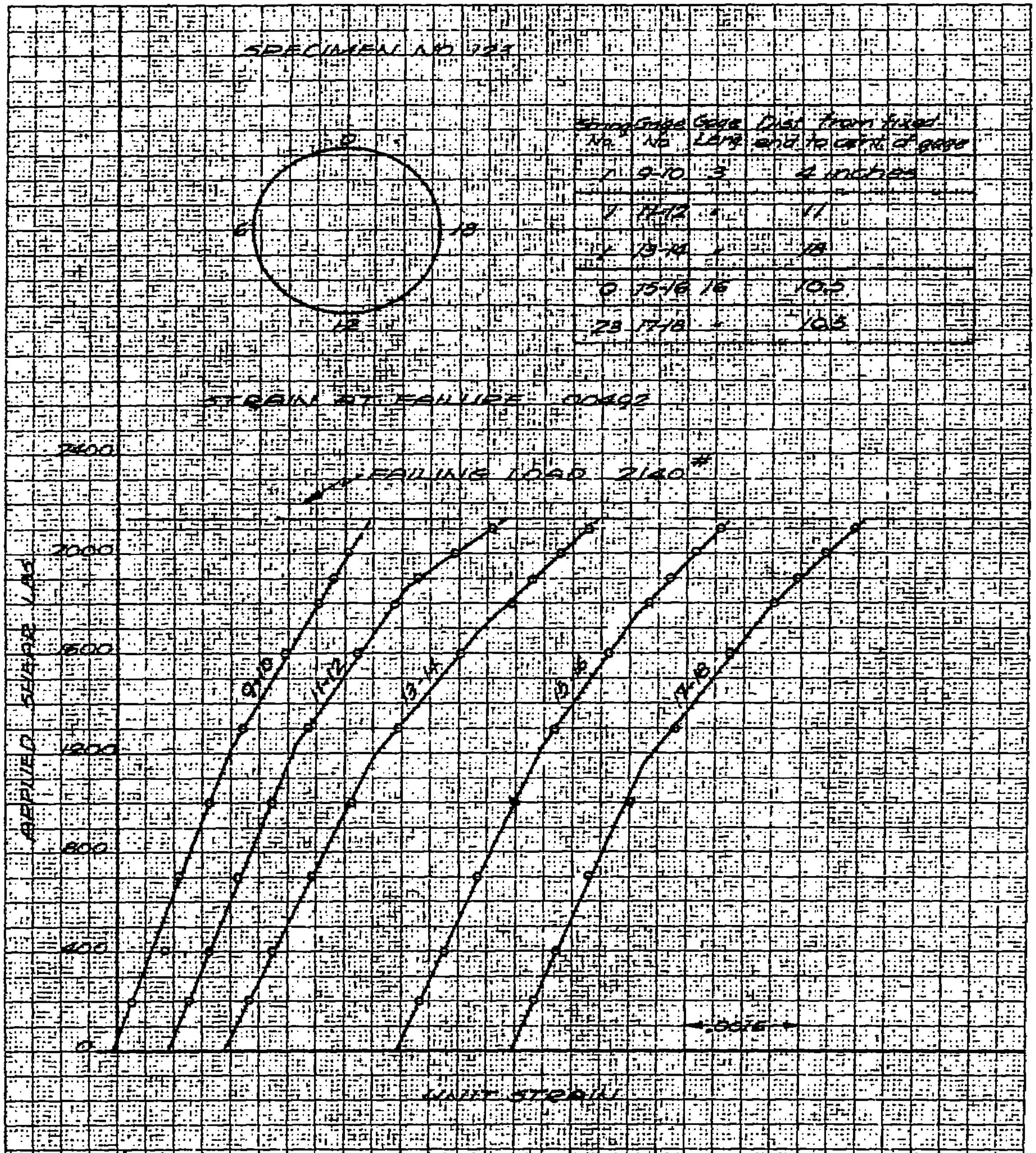
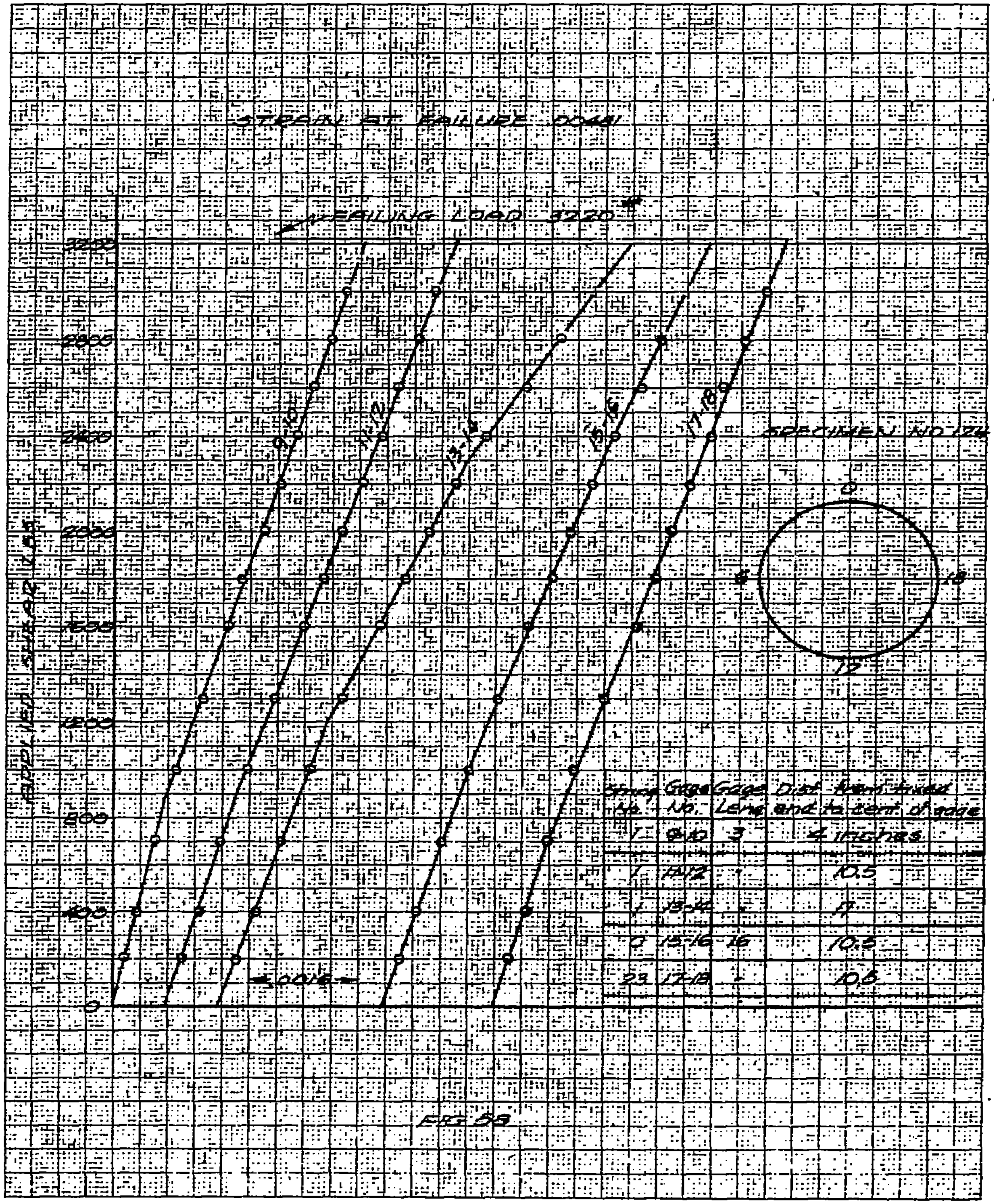
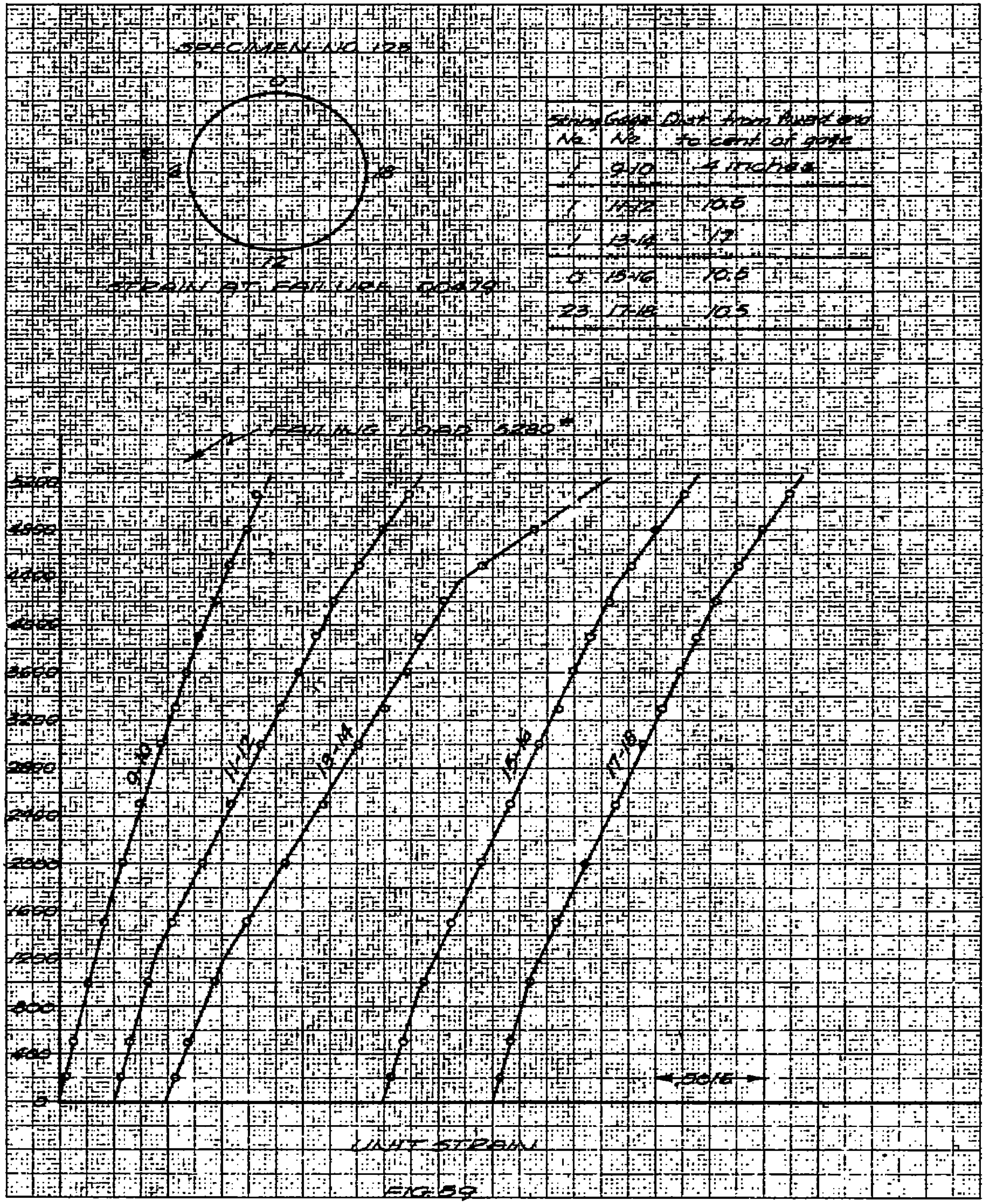

SPECIMEN NO. 123
Strain Gage No.
Gage No.
Gage Leng.
Dist. from fixed end to center of gage
1 9-10 3 2 inches
11-12 11
13-14 18
0 15-16 16 10.5
23 17-18 10.5
0
6
18
12
STRAIN AT FAILURE .00492
FAILING LOAD 2140#
APPLIED SHEAR LBS
2400
2000
1600
1200
800
400
0
.0015
UNIT STRAIN

FIG. 57


STRAIN AT FAILURE .0041
FAILING LOAD 3220#
3200
2800
2400
2000
1600
1200
800
400
0
APPLIED SHEAR LBS
9-10
11-12
13-14
15-16
17-18
.0016
SPECIMEN NO 124
0
6
18
12
Strap Gage Gage Dist. from fixed
No. No. Leng end to cent of gage
1 9-10 3 4 inches
1 11-12 " 10.5
1 13-14 " 17
0 15-16 16 10.5
23 17-18 " 10.5
FIG 58



String No.	Gage No.	Dist. from fixed end to cent of gage
1	9-10	4 inches
1	11-12	10.5
1	13-14	17
6	15-16	10.5
23	17-18	10.5

FIG. 59

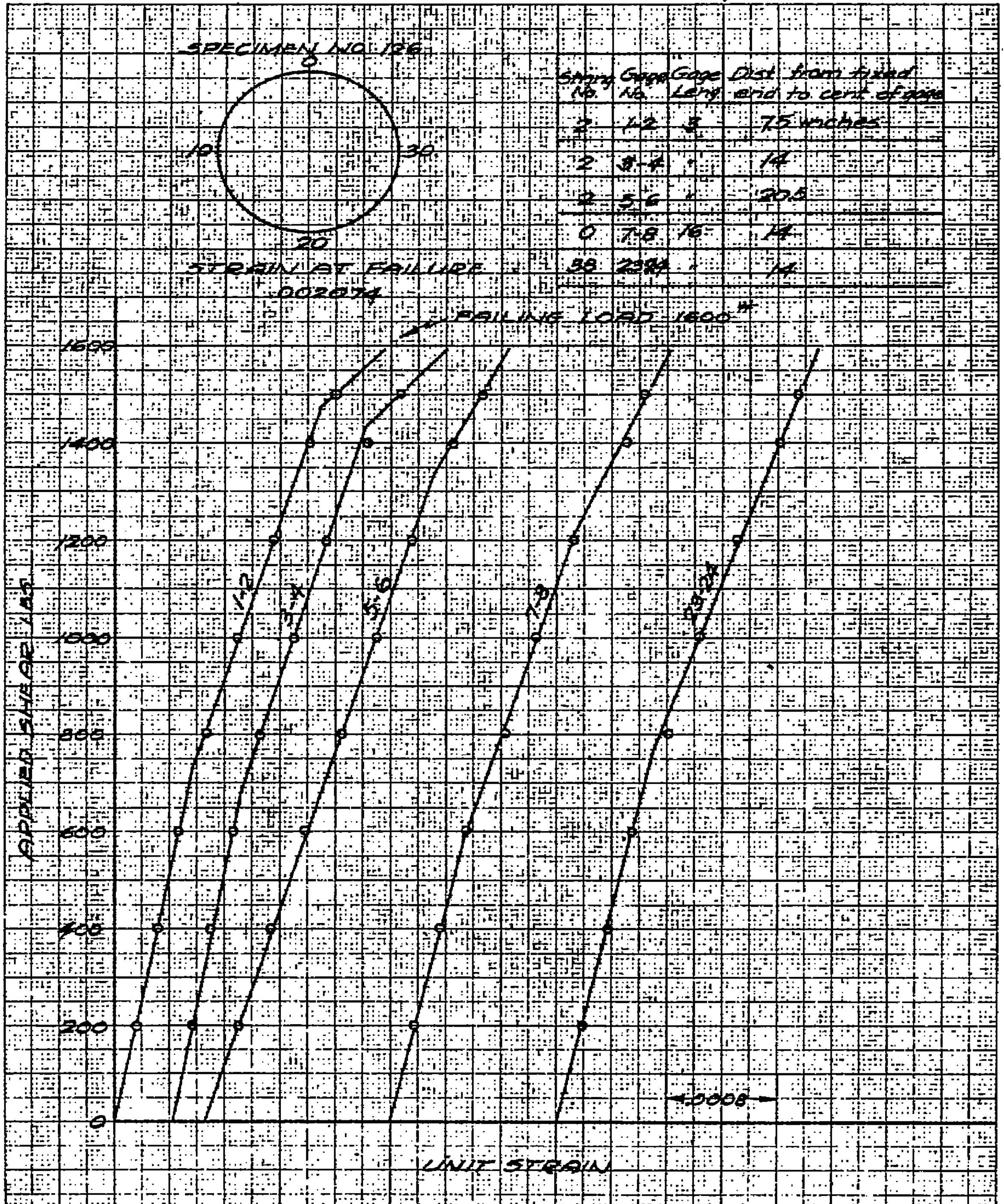
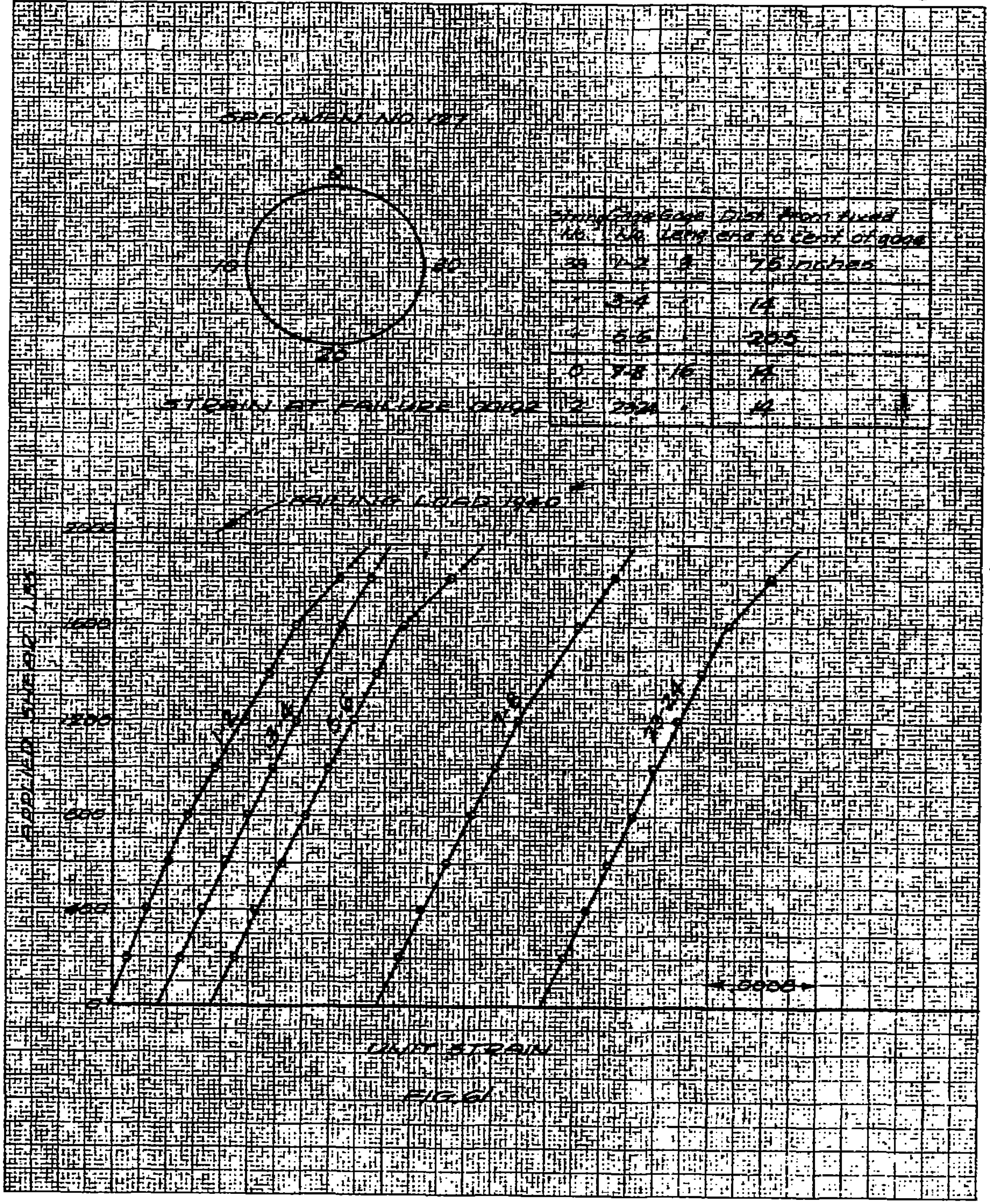

SPECIMEN NO. 126
0
10
30
20
STRAIN AT FAILURE
.002074
String No. | Gage No. | Gage Leng. | Dist. from fixed end to cent. of gage
2 | 1-2 | 3 | 7.5 inches
2 | 3-4 | " | 14
2 | 5-6 | " | 20.5
0 | 7-8 | 16 | 14
38 | 23-24 | " | 14
FAILING LOAD 1600#
1600
1400
1200
1000
800
600
400
200
0
1-2
3-4
5-6
7-8
23-24
APPLIED SHEAR LBS
.0008
UNIT STRAIN

FIG. 60


UNIT STRAIN
FIG. 61

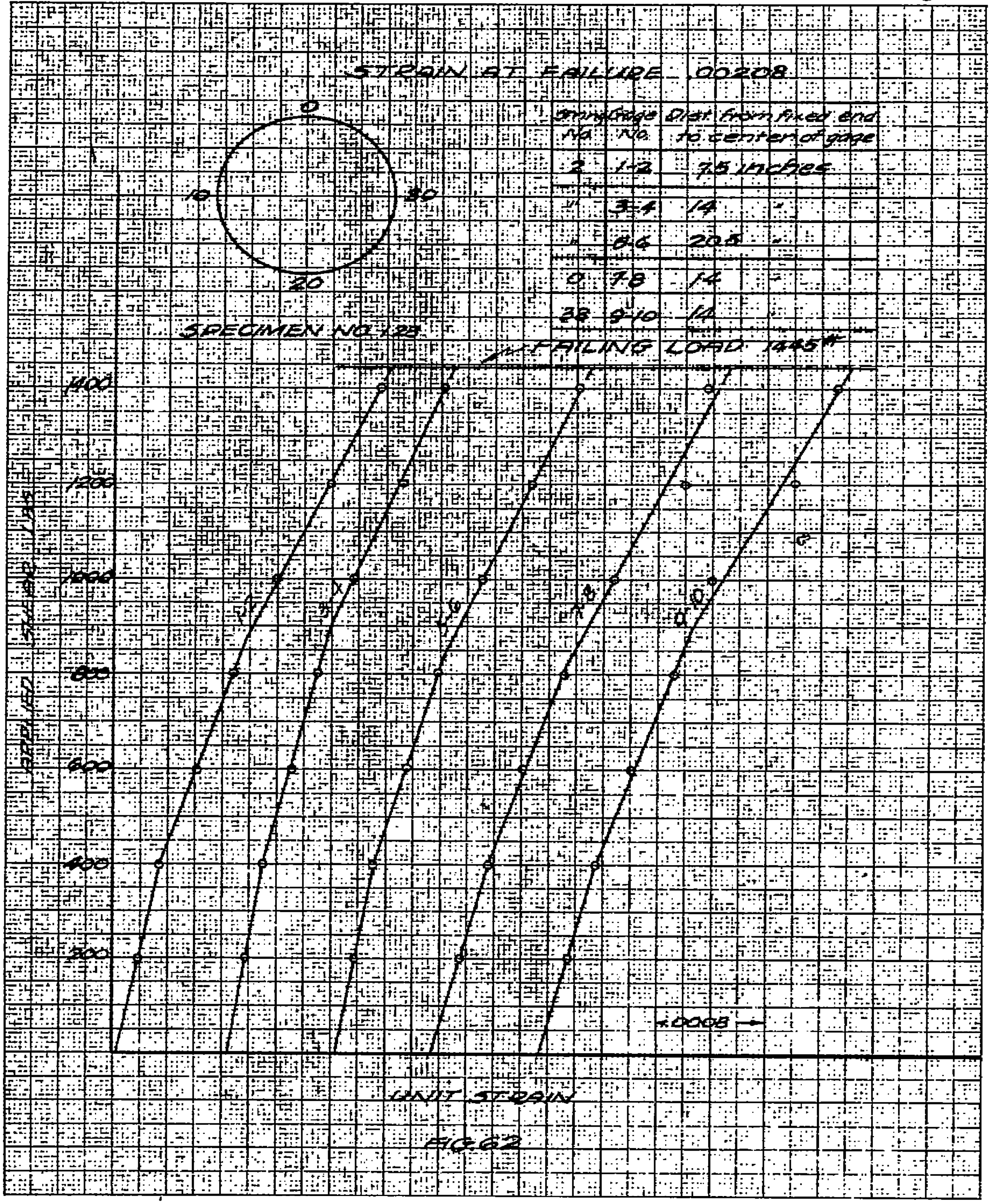

STRAIN AT FAILURE .00208
0
10
30
20
String No. | Gage No. | Dist. from fixed end to center of gage
2 | 1-2 | 7.5 inches
" | 3-4 | 14 "
" | 5-6 | 20.5 "
0 | 7-8 | 14 "
28 | 9-10 | 14 "
SPECIMEN NO. 128
FAILING LOAD 1445#
1400
1200
1000
800
600
400
200
APPLIED STATIC LOAD LBS
.0008
UNIT STRAIN

FIG. 62

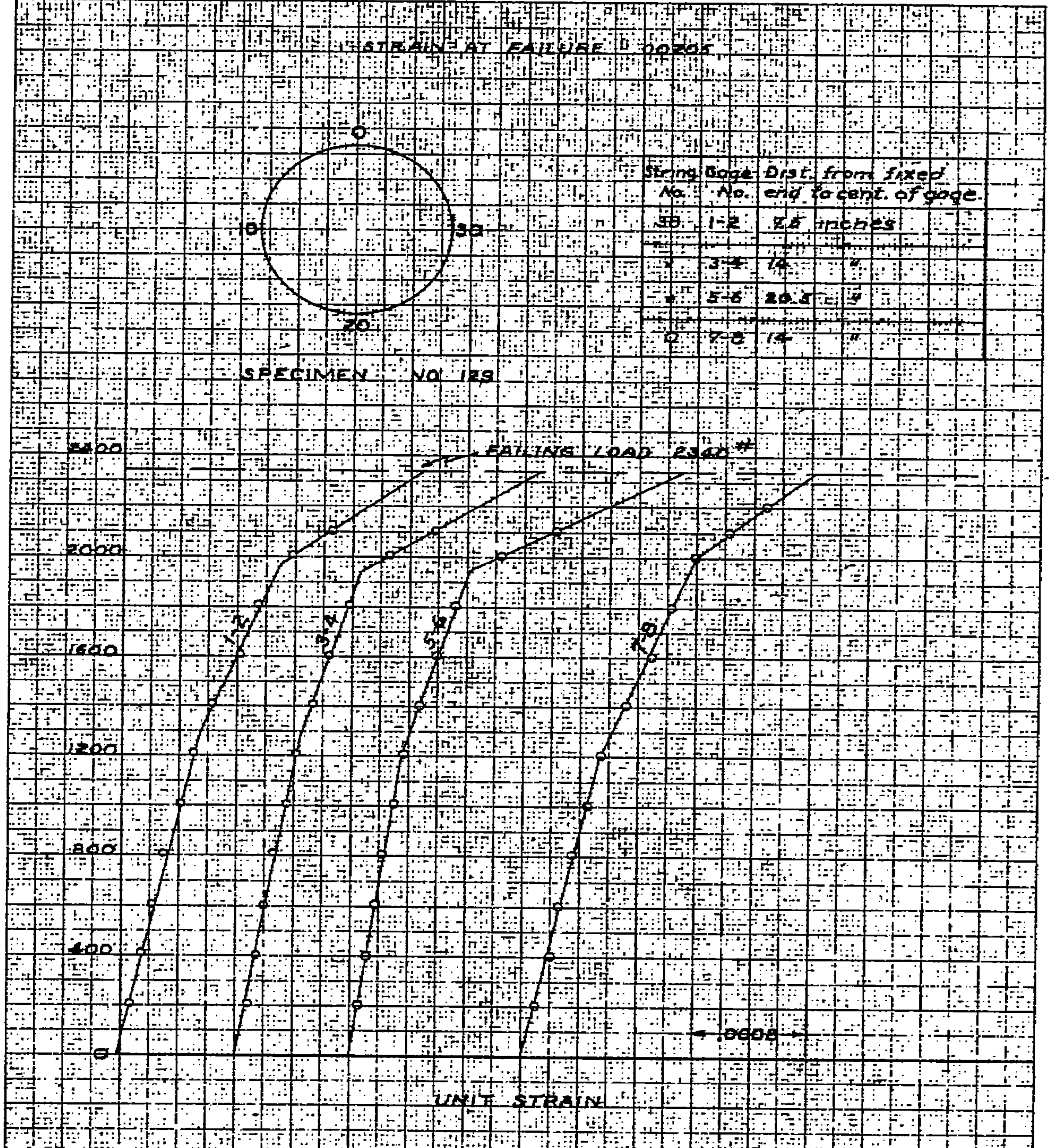
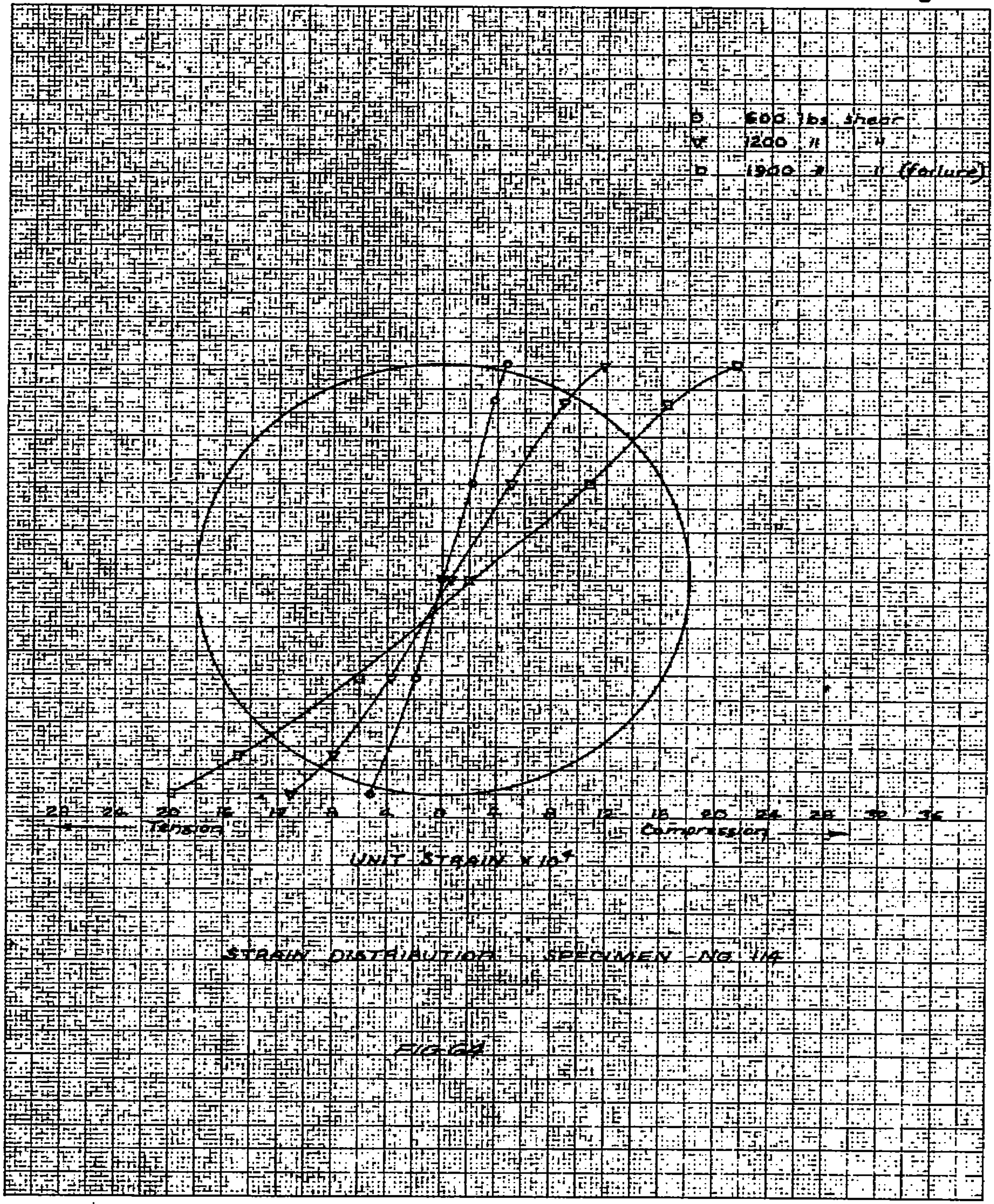
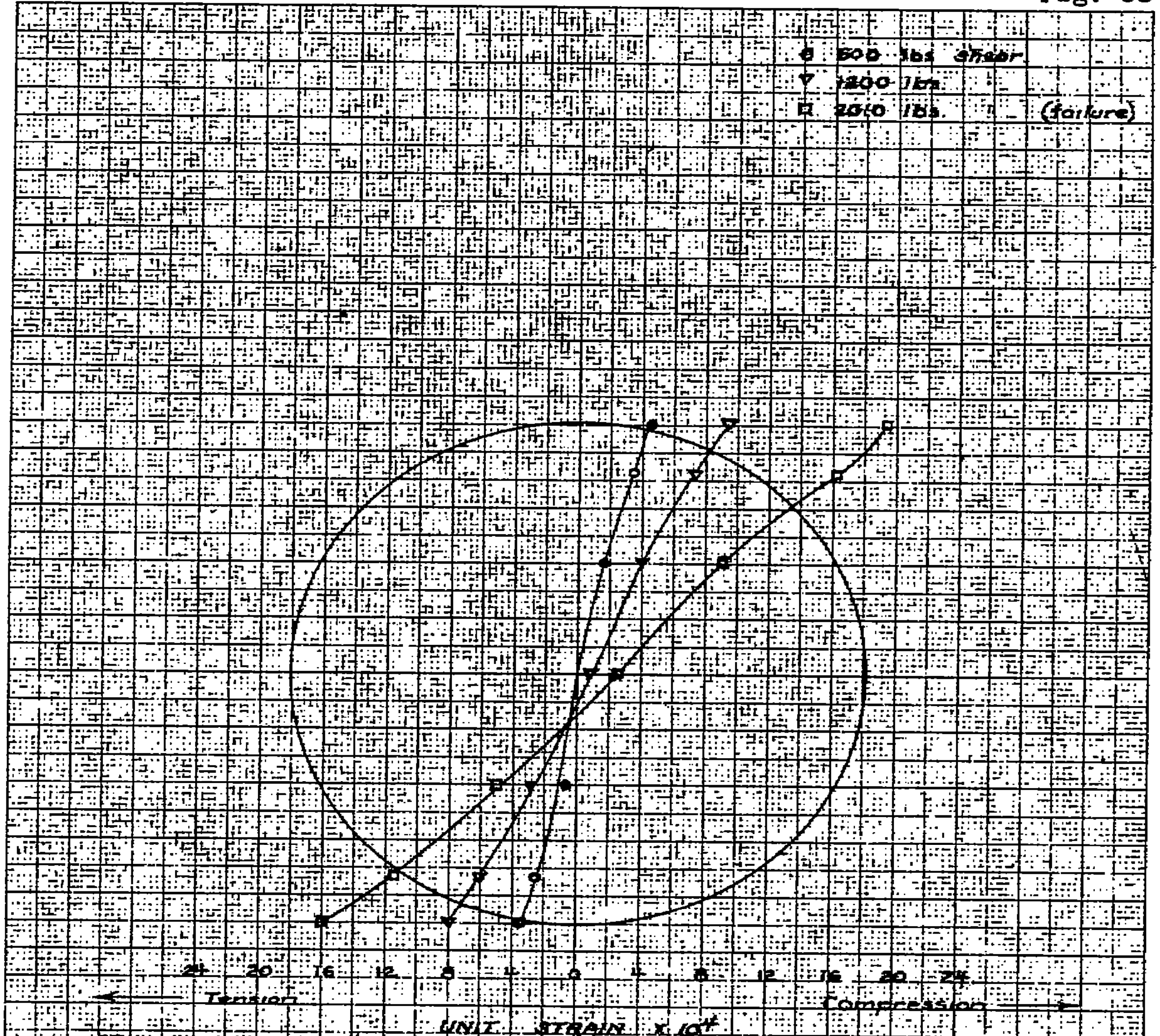

STRAIN AT FAILURE .00205
0
10
30
20
String No.
Gage No.
Dist. from fixed end to cent. of gage.
1-2 7.5 inches
3-4 14 "
5-6 20.5 "
7-8 14 "
SPECIMEN NO. 129
2400
2000
1600
1200
800
400
0
FAILING LOAD 2340 #
1-2
3-4
5-6
7-8
.0008
UNIT STRAIN

FIG. 63



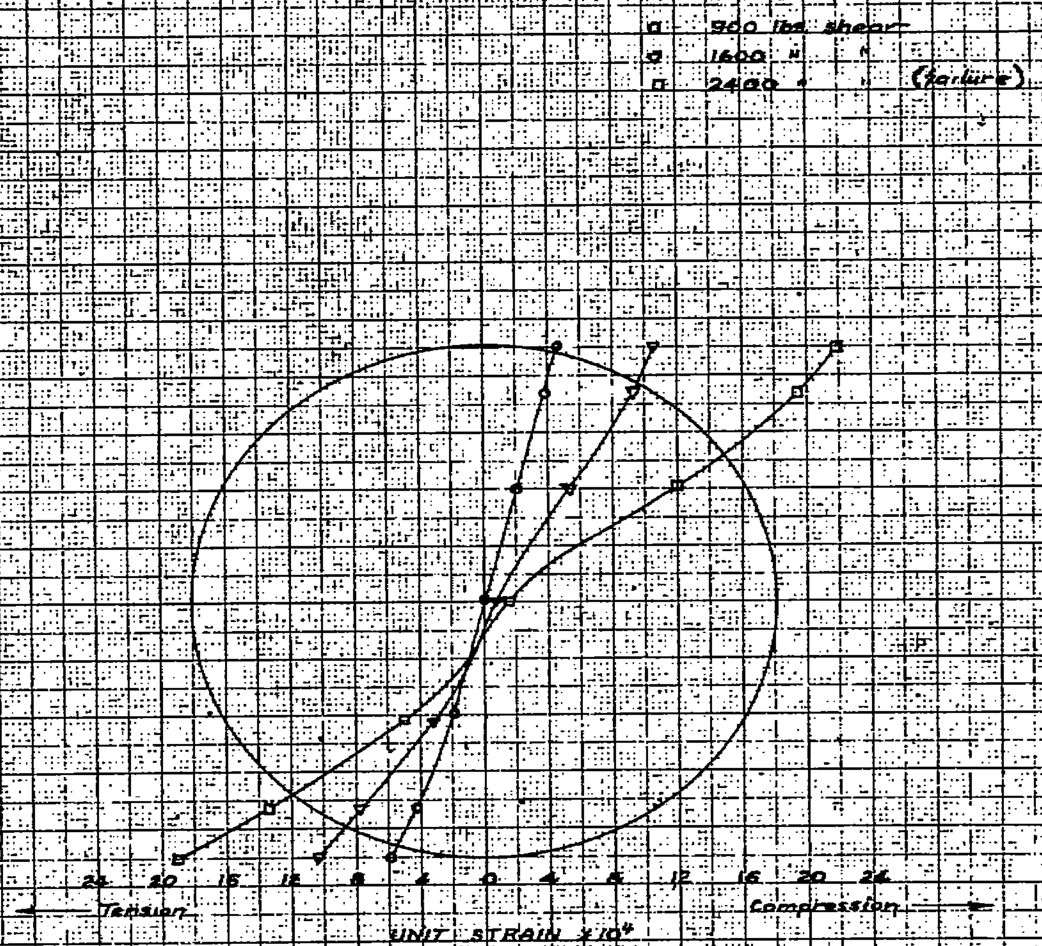
STRAIN DISTRIBUTION SPECIMEN NO 114

FIG 64



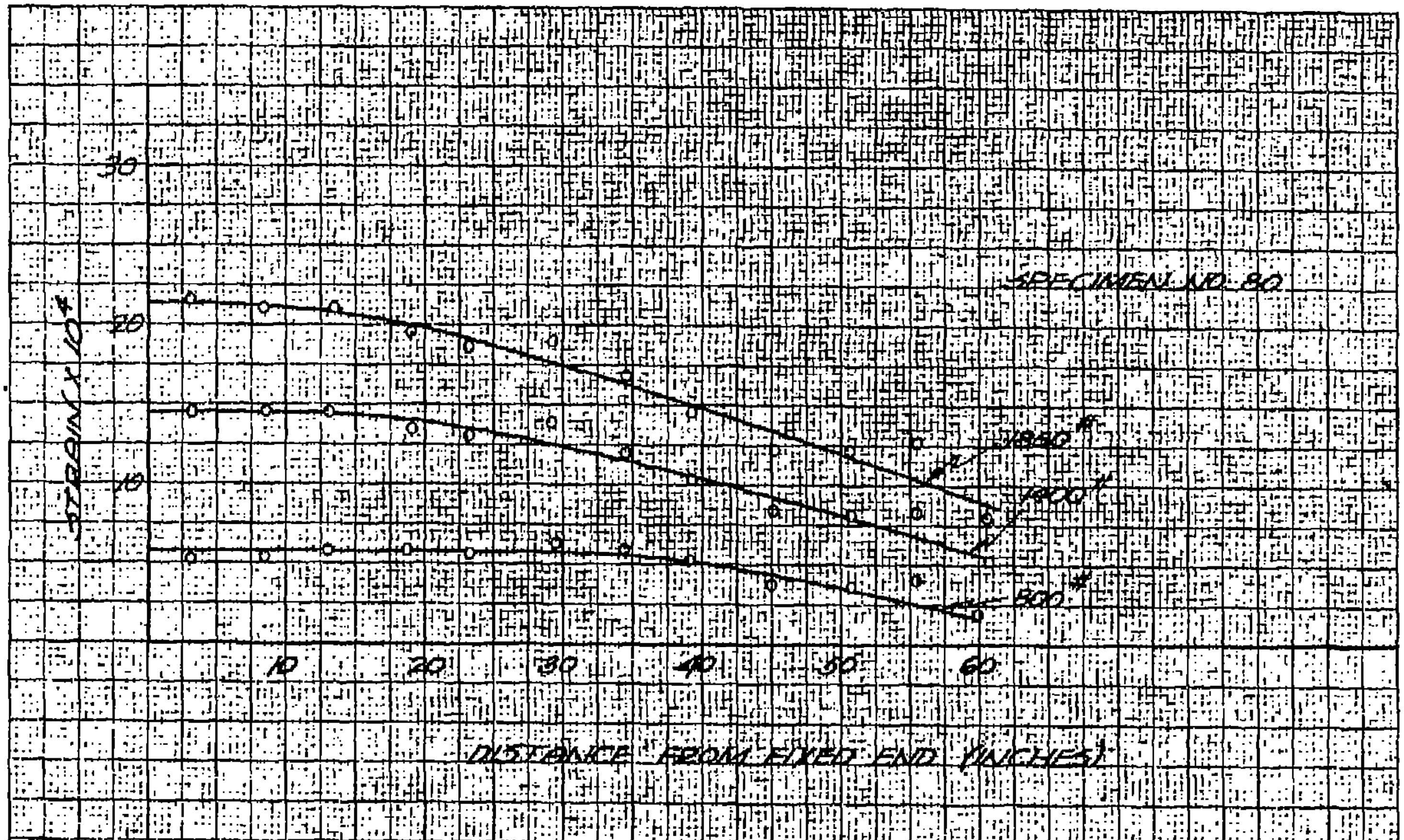
STRAIN DISTRIBUTION — SPECIMEN No. 115

FIG. 65



STRAIN DISTRIBUTION - SPECIMEN No. 116

FIG. 66

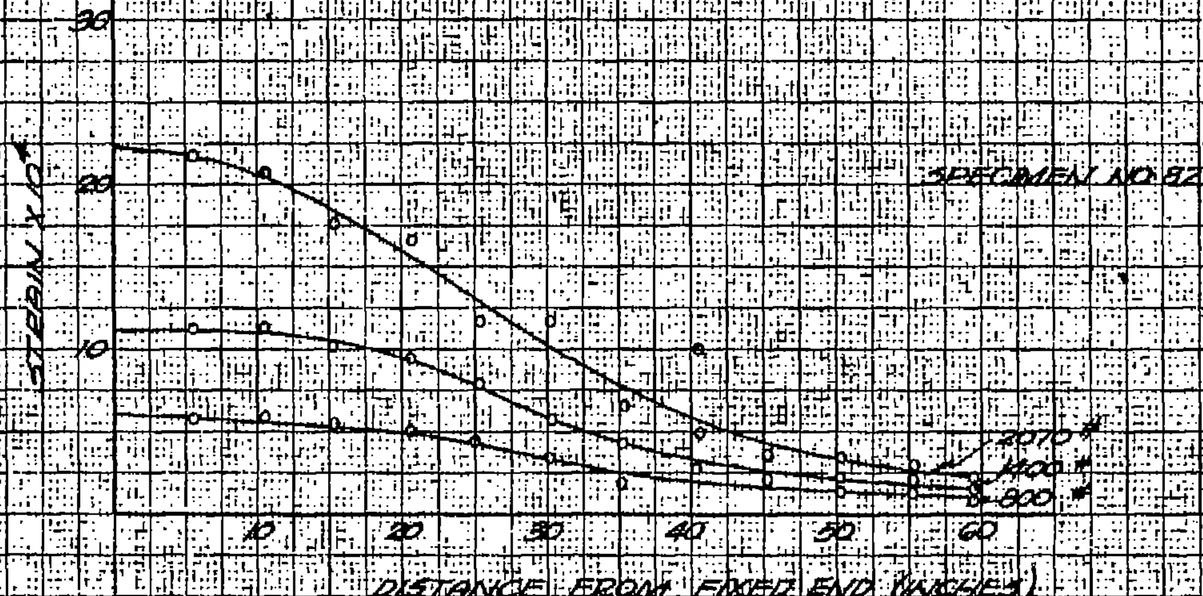


LENGTHWISE DISTRIBUTION OF STRAIN FOR VARIOUS LOADS

FIG. 67

LENGTHWISE DISTRIBUTION OF SHEAR FOR VARIOUS LOADS

FIG. 68



LENGTHWISE DISTRIBUTION OF STRAIN FOR VARIOUS LOADS

FIG. 69

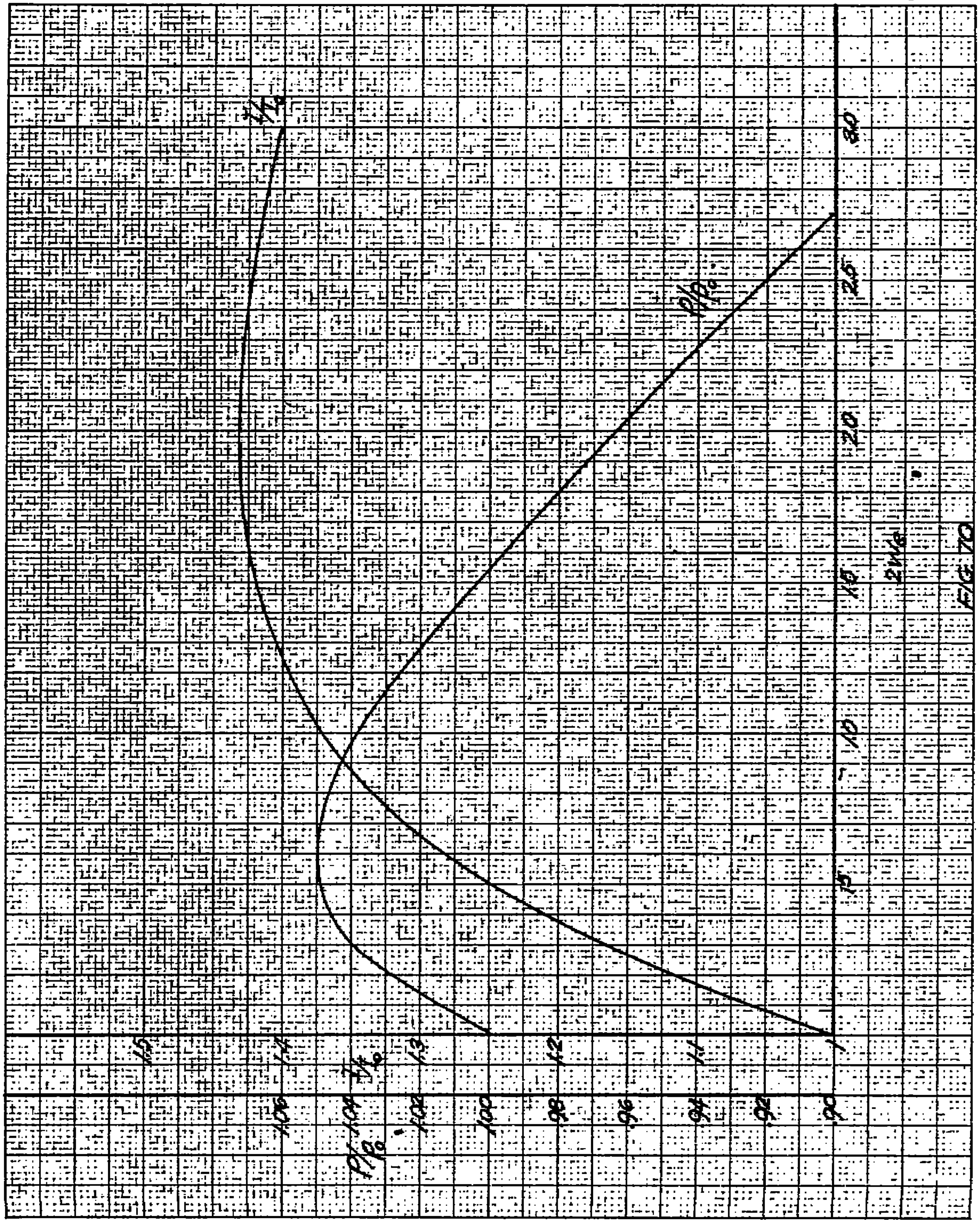


FIG 70

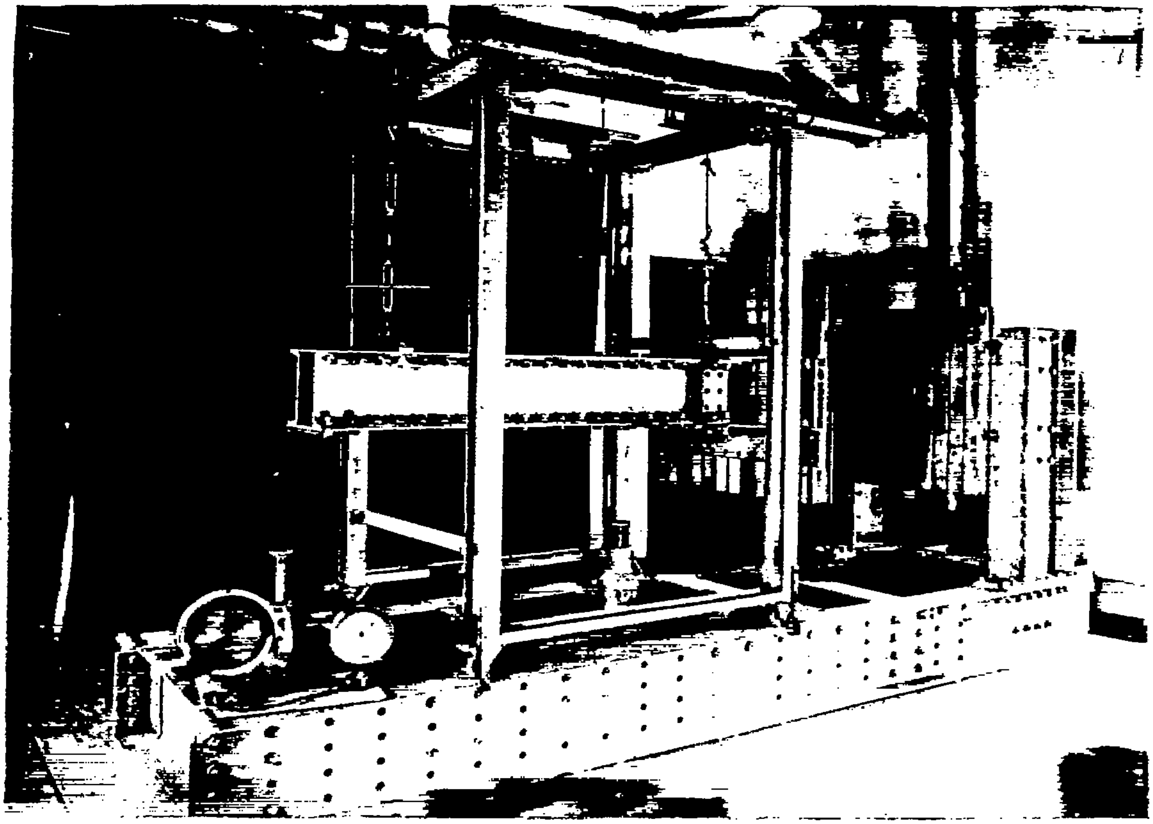


Fig. 71

Testing apparatus.

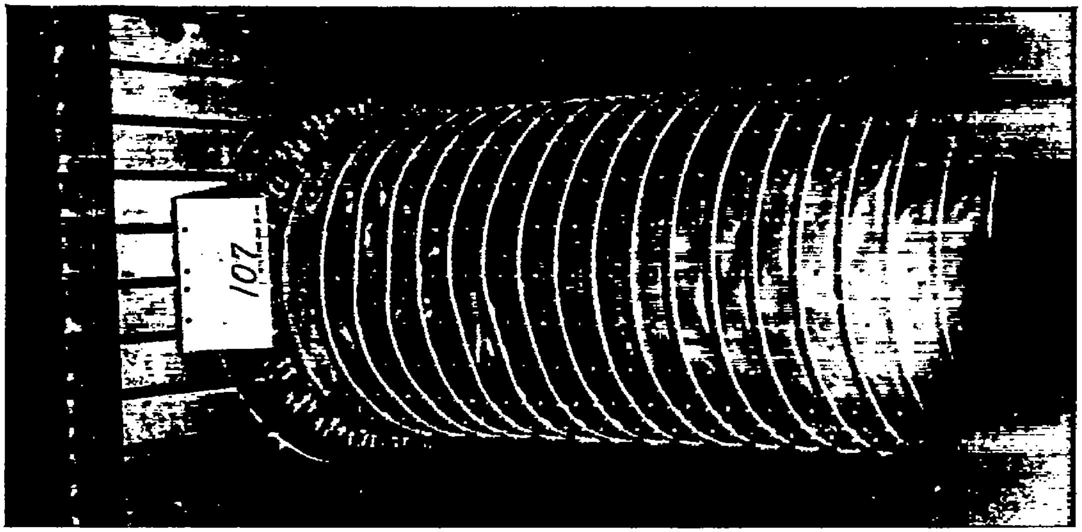


Fig. 72 (Specimen no. 107)

Top view of specimen which failed in compression. All specimens were loaded so that compression side was on top.

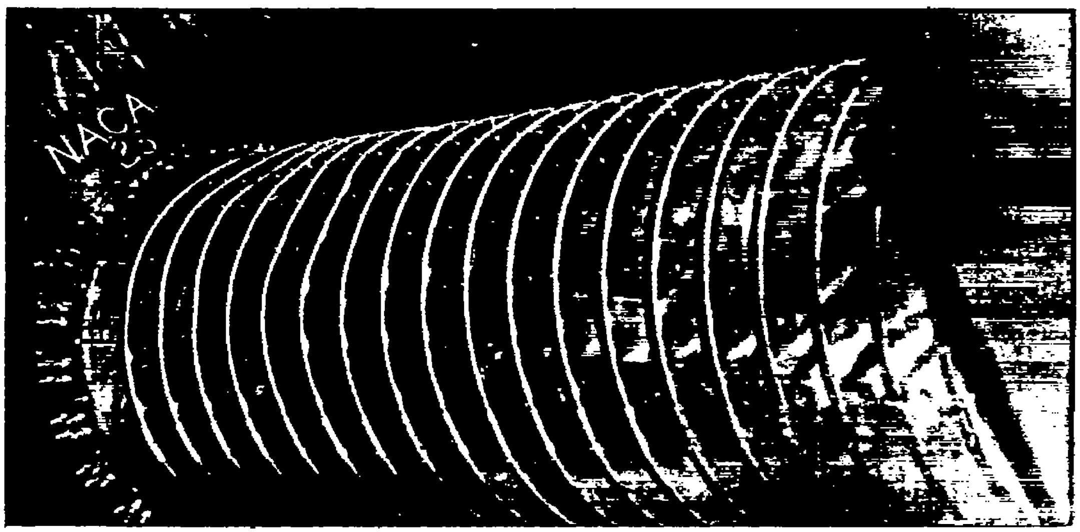


Fig. 73 (Specimen no. 107)

Side view of compression failure. Small buckles at sides appeared at failure.

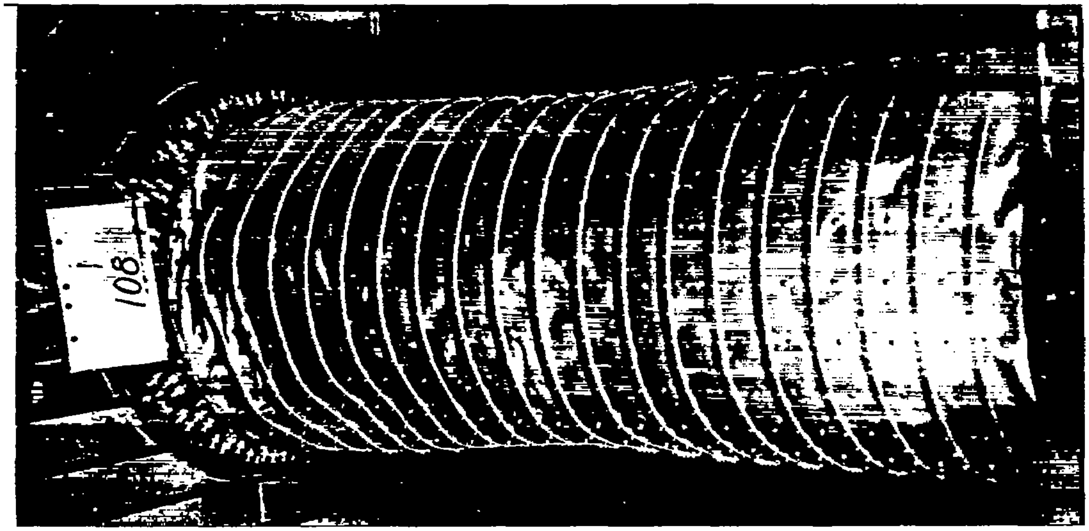


Fig. 74 (Specimen no. 108)

Top view showing compression failure. At failure, buckles extended slightly over the sides.

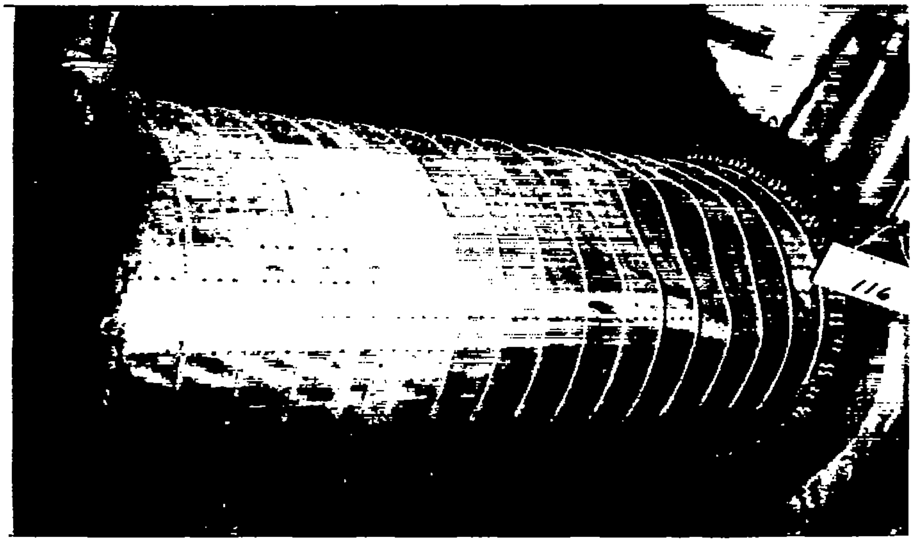


Fig. 75 (Specimen no. 116)

Failure Occurred by simultaneous bending and shear. Note shear buckles on side and compression buckle on top.

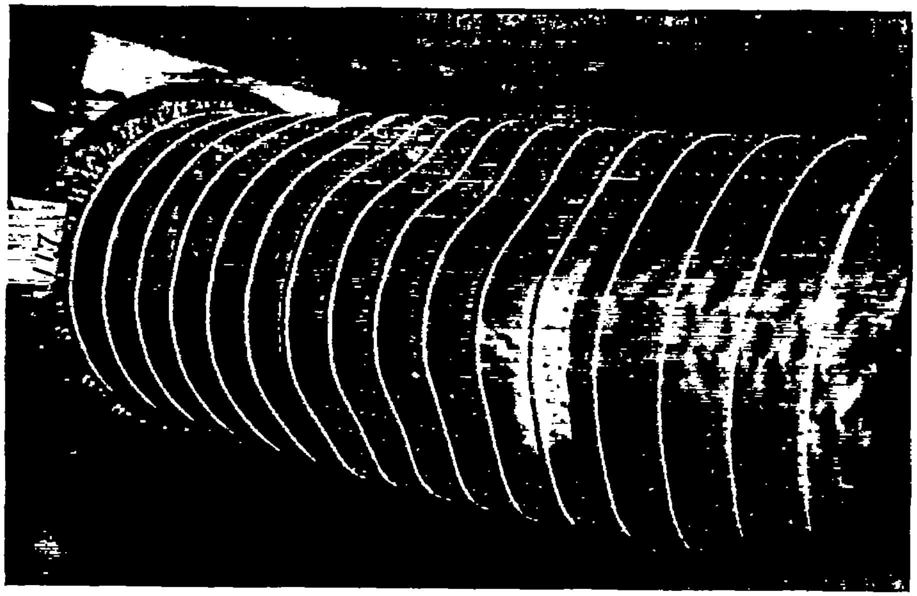


Fig. 76 (Specimen no. 117)

Top view of specimen which failed in shear. Note absence of compression buckles on top.

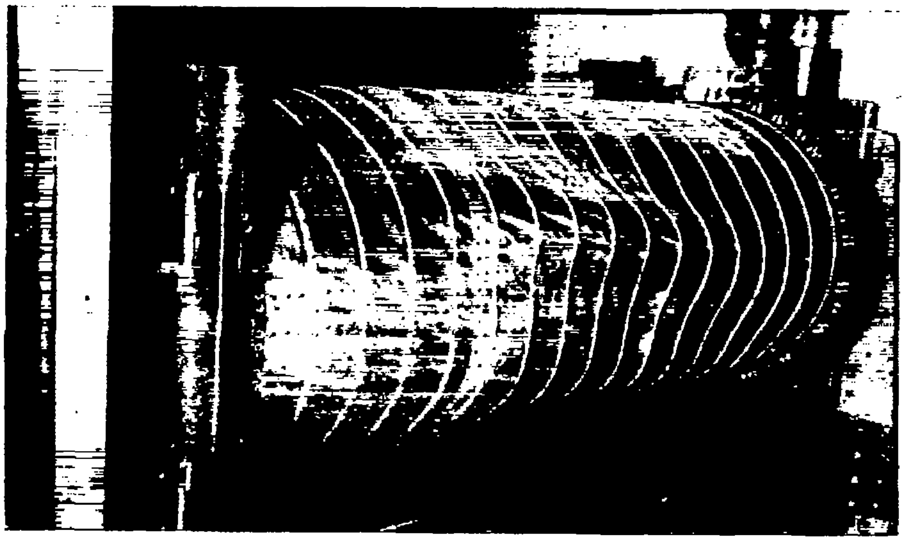


Fig. 77 (Specimen no. 117)

Side view of shear failure. Note that the shear buckles extend into the tension zone.

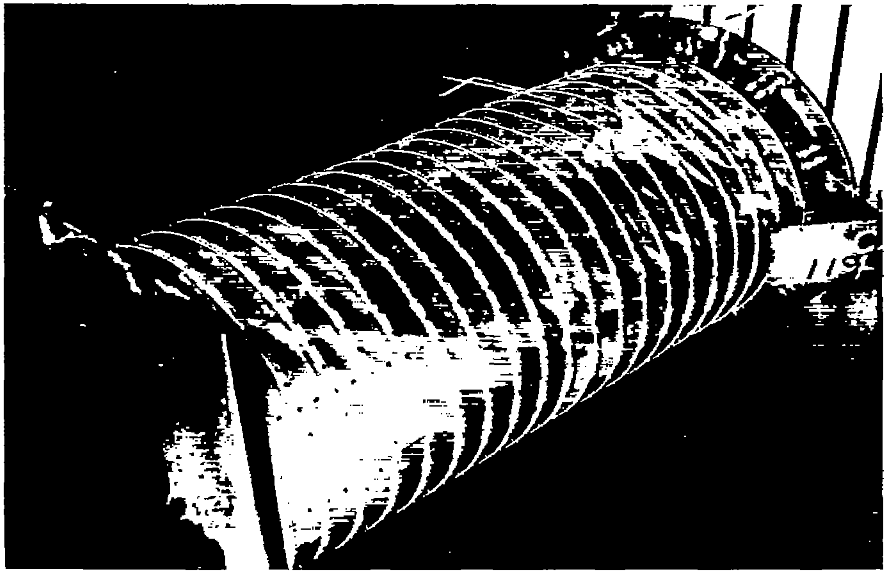


Fig. 78 (Specimen no. 119)

Compression failure. Note failure occurred over relatively small region near fixed end.

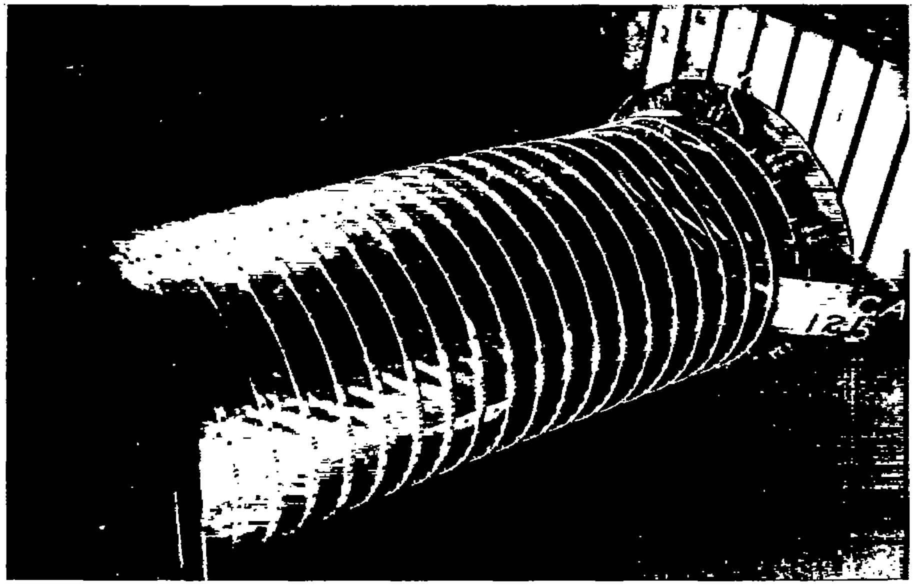


Fig. 79 (Specimen no. 121)

Compression failure.